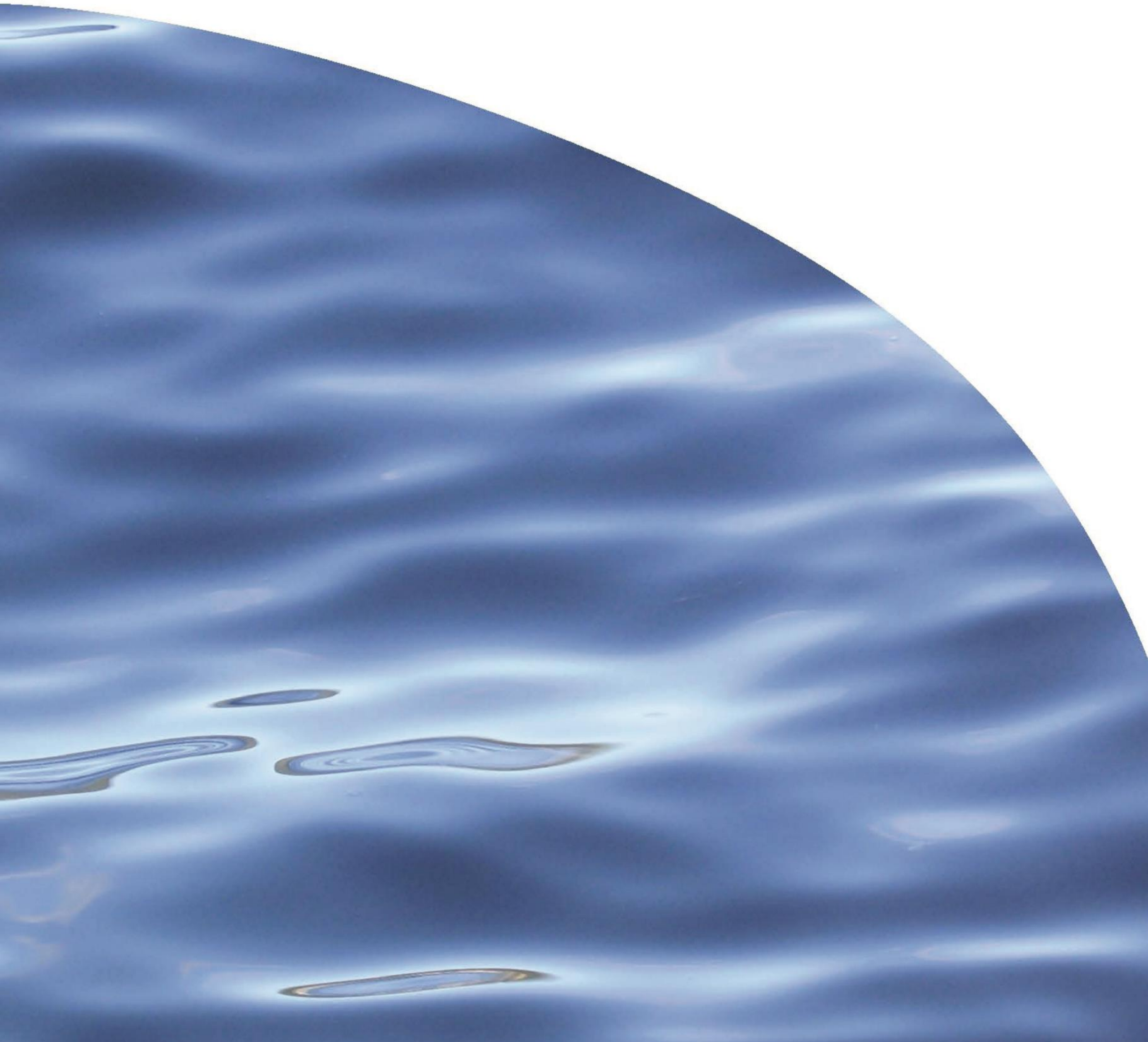
REPORT NO. 3056

POTENTIAL AQUACULTURE EXPANSION IN THE EASTERN BAY OF PLENTY - A HIGH-LEVEL SCOPING STUDY OF ENVIRONMENTAL ISSUES



POTENTIAL AQUACULTURE EXPANSION IN THE EASTERN BAY OF PLENTY - A HIGH-LEVEL SCOPING STUDY OF ENVIRONMENTAL ISSUES

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EXECUTIVE SUMMARY

The Bay of Plenty Regional Council (BOPRC) wish to consider the provision of new aquaculture space close to a proposed Opotiki harbour entrance. Cawthron Institute was asked to provide a high-level desk-top assessment of issues relating to the water column and connectivity between potential aquaculture development sites. We consider a range of issues that may have implications for environmental health in the area, and for operational aspects of the potential aquaculture sites. At this early stage in the proposal, it was appropriate to focus on key issues relevant to the siting of, and potential limits to, aquaculture expansion in the area.

In formulating an initial assessment of suitable areas for consideration, four large (c. 3,700 ha) aquaculture areas and one smaller (c. 1,000 ha) area have been considered. Potential aquaculture area locations were selected based on criteria presented to us by BOPRC, and the spacing between the areas was chosen to reduce the effects of phytoplankton depletion between mussel farming sites.

In order to reduce a range of potential issues if the sites are developed, between-site spacing was informed by connectivity modelling in the region. The modelling was used to infer potential magnitudes of effects associated with biosecurity, interception of mussel spat, and phytoplankton depletion. All modelled locations had relatively low water-current velocities (mean currents of 4–6 cm/s) when compared to existing inshore mussel and finfish farms in New Zealand.

Connectivity modelling released virtual particles from within potential aquaculture areas and showed that typically, less than 10% of released particles interacted with other areas after two days. This result suggests that potentially harmful marine organisms (HMOs) with short propagule (e.g. larvae, spores) durations would have limited ability to spread between proposed farming areas. It also implies that recovery of grazed phytoplankton populations is likely, given doubling times are typically around two days. Our findings, pertaining to a total shellfish aquaculture development of up to 19,700 (including an existing 3,800 ha site), are also consistent with more complex modelling undertaken by Longdill et al. (2006) who show the cumulative effects of up to 18,900 ha of mussel culture, albeit in a wider region to the west of that considered here.

The connectivity modelling results also show that there is an increased probability of connection between the aquaculture areas (e.g. up to c. 45% for proximate sites) for long-dispersing (> 14 days to settlement) organisms (such as mussel spat, or HMOs) considered here. This suggests that some interception of spat and potential for spread of long-dispersing organisms is possible. Both issues are potentially manageable; in the case of spat, an increased spawning population (i.e. cultured mussels) will likely mitigate effects, whereas for HMOs appropriate management plans will be required to mitigate risks.

A review of harmful algal blooms (HABs) was also undertaken. The Bay of Plenty has a long history of contamination of local shellfish (surf clams/tuatua and green-lipped mussels) by paralytic shellfish poisoning (PSP) toxins. Approximately 30 cases of human PSP illness have been documented in the region in recent years due to consumption of surf clams (tuatua). This will be an important quality assurance issue for the industry as it is highly likely it will affect offshore cultured shellfish in the region. Contamination episodes may be expected annually but will probably be of relatively short duration. Similarly, if finfish farming is considered in the area, there is also the potential for ichthyotoxic (fish-killing) phytoplankton species to affect cultured fish. However, the risks to finfish culture are probably lower in these sites than in farms in sheltered inshore areas elsewhere in New Zealand. Management of effects from HAB species on fish and shellfish culture is common and successful in nearshore aquaculture. Although extensive offshore aquaculture may present some new challenges, we consider that HAB issues can be managed with appropriate monitoring and mitigation procedures.

Based on this preliminary assessment, it appears that a combination of large new aquaculture areas (possibly up to the 16,000 ha considered here) may be able to be managed appropriately to address potential HAB, plankton depletion, spat, and biosecurity issues. However, it is important to understand that following limitations apply to this scoping study:

- this is a preliminary high-level assessment and there was little information available on the site-specific characteristics (e.g. seabed habitats) or the potential mix of species that could be cultured in future
- only high-level reviews of available information on HABs, HMOs, spat connectivity and carrying capacity were undertaken
- species-specific effects are also possible; although we focus on shellfish here, if large scale finfish aquaculture was considered for the region the potential for other issues are likely and would also need to be considered in more detail.

Therefore, a detailed assessment of site- and species-specific effects would be required if any of the potential areas presented here were to proceed to an application for use as aquaculture sites. Some gaps also exist in our understanding of long-term effects from aquaculture, particularly in this region in which limited aquaculture development has occurred to date. Hence, if substantial new aquaculture areas are considered for development, it would be prudent to consider a staged approach that would allow for appropriate environmental assessments to occur as development proceeds.

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1. INTRODUCTION

The Bay of Plenty Regional Council (BOPRC) wish to consider the potential for new aquaculture space in the eastern Bay of Plenty (Figure 1) as part of the Opotiki Harbour Development Project, to inform the case for a new harbour entrance at Opotiki. Cawthron Institute was asked to provide a high-level desktop assessment of issues relating to the water column and connectivity between potential aquaculture development sites. We consider a range of issues that may have implications for environmental health in the area, and for operational aspects of the potential aquaculture sites.

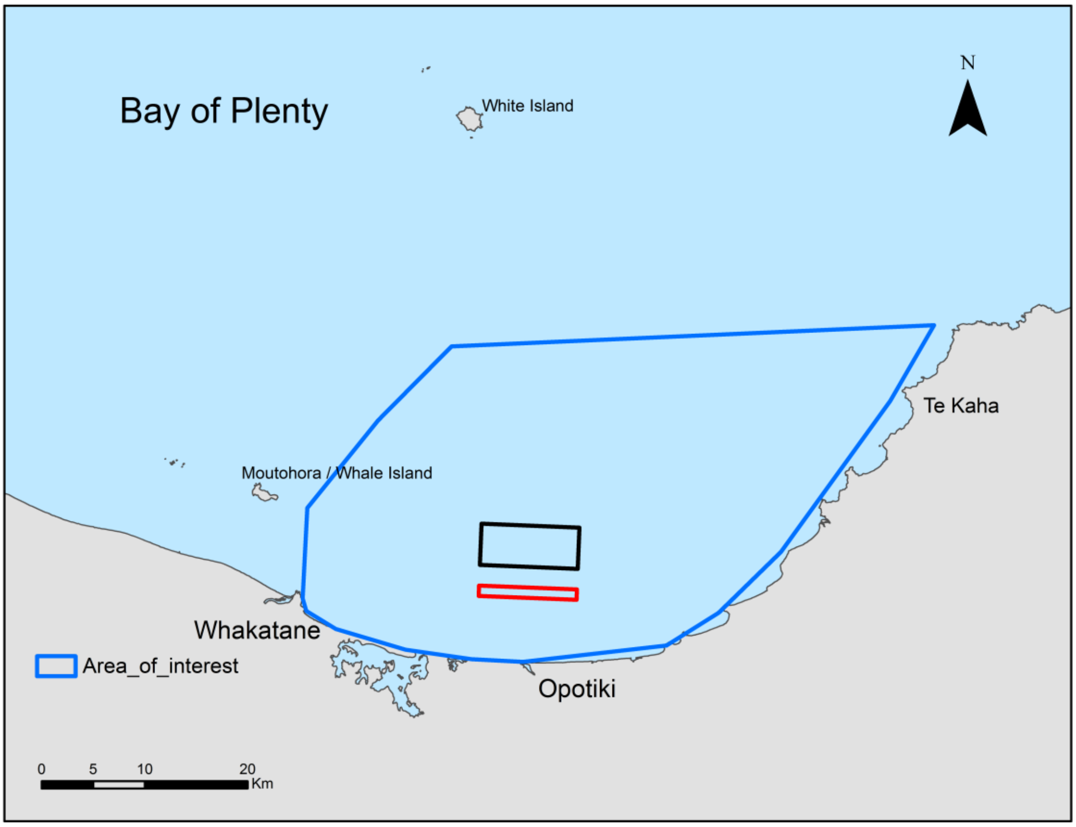

Figure 1. Approximate area of interest (enclosed by blue line) for potential new sites in the eastern Bay of Plenty, showing existing Eastern Seafarms Ltd. (ESL) site (black rectangle, north) and a previously declined spat catching site (red rectangle, south). Note that the proposed new port will be located at Opotiki, directly to the south of the existing ESL site.

In meeting with BOPRC, the potential use of new aquaculture space was discussed. It was noted that a wide range of species could be considered, including shellfish, finfish and/or seaweed. The environmental issues relating to farming these species are comprehensively addressed in the Ministry for Primary Industries' overview of ecological effects document (MPI 2013a) and other previous reviews (e.g. Forrest et al. 2007; Keeley et al. 2009). At this early stage in the proposal, a focus on key issues relevant to the siting of, and potential limits to, aquaculture expansion in the area was agreed as the scope of this report (Table 1). The key issues identified were:

- carrying capacity of shellfish farming through competition for food (e.g. plankton and other seston) from an increased population of filter feeding organisms (i.e. cultured mussels) (see Chapters 3 and 4)
- interception of spat (juvenile mussels) supply, to existing natural populations, and to existing or future aquaculture sites (see Chapter 4)
- exposure of farmed organisms and farming structures to harmful marine organisms (HMOs), and the potential of additional aquaculture to facilitate the spread HMOs (see Chapters 5 and 6)
- exposure of farmed organisms to harmful algal blooms (HABs) (see Chapter 7).

Table 1. Summary of information requested by Bay of Plenty Regional Council and the relevant sections in this report. Bracketed names refer to report authors that contributed to those section.

Information requested	**Section addressing information (author)**
Identify potential new farm space within the constraints provided by BOPRC (e.g. maximum bathymetry, distance from Opotiki)	Chapter 3 Physical environment (Knight & Vennell) and Chapter 4 Carrying capacity (Knight)
Estimate physical connectivity of the potential new marine farming areas with the existing consented space and give consideration to chlorophyll-*a* depletion, spread of marine pests and diseases and interference with spat-catching activities	Chapter 5 Physical connectivity (Vennell & Knight)
An overview of risks posed by threats to biosecurity and harmful algal blooms	Chapter 6 Biosecurity considerations (Forrest) and Chapter 7 Harmful algal blooms review (MacKenzie)
A high-level assessment of knowledge gaps and additional information that would be required to fully assess the potential environmental effects of the proposed activities based on experience with other developments	Chapter 8 Gap analysis and likely requirements for further development (Taylor)

1.1. Potential aquaculture sites

We provide some background to the physical characteristics in the following section (Chapter 3). This provides context regarding the suitability of the area for aquaculture.

Potential new aquaculture sites were selected according to criteria provided to BOPRC by industry representatives. These specified that farms would ideally lie between 30 m and 50 m water depth and be located no further than 50 km from the Opotiki Harbour entrance. Because this project is focussed on the Opotiki harbour development, it does not consider other potentially suitable sites that may be better served by other harbours (e.g. to the west of Moutohorā Island). In identifying potential sites, we have also considered the magnitude of predicted chlorophyll-*a* depletion effects and previous estimates of effects from mussel culture, which is detailed in the Carrying Capacity section of this report (Chapter 4). Further testing and refinement of the locations of these sites was updated in the Physical Connectivity modelling section (Chapter 5).

1.1.1. Site selection

Five provisional sites around the existing consented Eastern Seafarms Limited (ESL) aquaculture area (Farm 3 in Figure 2) were considered as potential aquaculture sites (farms 1-2 and 4-6 in Figure 2, see also Table 2). The sites include an inshore site (~1,000 ha) that was previously considered in a resource consent application to BOPRC, but was declined due to potential fisheries effects (Farm 4 in Figure 2). An additional outer site in up to 65 m of water, was also proposed by BOPRC for consideration, as industry suggested there may be potential to farm in waters deeper than 50 m (Farm 2 in Figure 2).

To establish the suitability of horizontal spacing between farms, we undertook a physical characteristics analysis (Chapter 2), which showed that water currents were typically aligned with the shoreline. Consequently, we employed a smaller cross-shore farm spacing (c. 2 km). We also considered the magnitude of predicted chlorophyll-*a* depletion effects, which decrease to about 0.15 mg/m^3 within approximately 3-4 km of the existing farm (based on model images presented in Longdill et al. 2006, refer Section 3.2.1).

Initial model runs indicated that the north-west corners of Farms 5 and 6 had greater connectivity with Farms 1 to 3. Consequently, the shapes of theses farms were revised (skewed red polygons 'Version 2' outlines, see Figure 2). This alteration slightly reduced the physical connectivity between these farms. All results shown for farms 5 and 6 are for the revised 'Version 2' farm shapes.

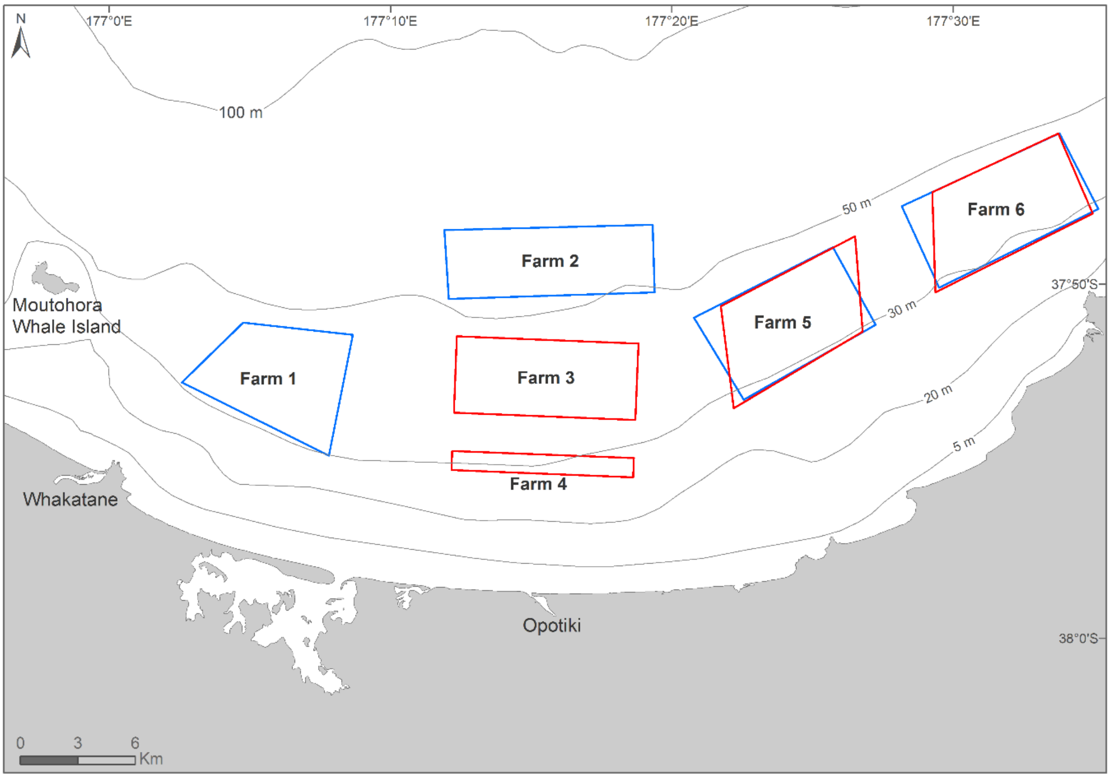

Figure 2. Potential aquaculture areas modelled for hydrodynamic connectivity. Farm 3 (red) is an existing consented area. Blue outlines show initial proposed large additional areas. An initial model run used these blue polygons. All subsequent model runs used the red skewed 'Version 2' polygons for farms 5 and 6, along with the Version 1 for all other farms.

Table 2. Potential and existing aquaculture sites with number, size, and dimensions used in model Initial and Final Farm sizes and shapes. Only farms 5 and 6 were altered after initial runs to create a "Version 2" of these farms.

Model run	Farm number	Size (Hectares)	Approximate Dimensions
Initial	1	3600	7 km by 5.5 km
	2	3800	10 km by 3.5 km
	3 - Eastern Seafarms	3798	9 km by 4 km
	4	954	9 km by 0.8 km
	5	3850	7.9 km by 4.5 km
	6	4100	9.3 km by 4.6 km
Final	1	3600	7 km by 5.5 km
	2	3800	10 km by 3.5 km
	3 - Eastern Seafarms	3798	9 km by 4 km
	4	954	9 km by 0.8 km
	5 - version 2	3750	7.8 km by 4.5 km
	6 - version 2	3800	8.5 km by 4.6 km

These potential farm locations represent the type of development that BOPRC has requested be investigated. However, these preliminary locations could be altered, particularly if an area less than the total is considered for development. For example, removing Farm 6 would allow Farm 5 to move further from Farm 3, reducing the connectivity between them, but at a cost of longer travel times to Farm 5. As discussed in Section 4, increasing the between-farm spacing is generally an effective means of mitigating a range of ecological effects and hence should be considered if a smaller area is considered.

2. PHYSICAL ENVIRONMENT IN THE REGION

The physical environment plays a critical role in determining the capacity of a region to support aquaculture and can have important operational implications. Physical factors that may affect the feasibility of aquaculture development include currents, temperature and waves. Here we provide a high-level characterisation of these in the region.

2.1. Water currents

Water currents are critically important in distributing and diluting farm-related wastes from aquaculture. They can also affect the supply of food for filter-feeding aquaculture species and the supply of oxygen to finfish species. Thus water currents can affect the suitability of a site for particular types of aquaculture.

The main currents within the BOP appear to be an extension of the East Auckland Current (EAC); consequently the entrainment of oceanic water into the bay is likely to be driven through this current (Ridgeway & Greig 1986). More recent research showed that wind and other circulation drivers (including tides) appear to dominate current flows in the area (Heasman et al. 2009). This research showed a predominantly westerly flow near the existing ESL farm, consistent with the findings of Ridgeway and Grieg (1986) for the outer bay.

Heasman et al. (2009) also observed that tides had a minor influence on overall currents within the bay. This is consistent with the findings in a previous study (Black et al. 2005), which found maximum tidal flows of up to 10 cm/s, whereas total current flow has been shown to exceed 25 cm/s. These currents are of a similar magnitude to those observed at inshore mussel farm sites around New Zealand. The currents described by Heasman et al. (2009), are also of a similar magnitude to the modelled currents used in this report.

A two-dimensional depth-averaged hydrodynamic model was used to better understand the likely water current patterns at the proposed sites. Details of the model are given in Appendix 1. A snapshot of the modelled currents, at every second grid point of the model from the first day of the indicated month, illustrates the variability and complexity of horizontal flows in eastern Bay of Plenty (Figure 3). The currents include the effects of winds, tides and the larger scale circulation. The upper plot, January 2010, illustrates weak variable currents over most of the area. April 2010 shows strong eastwards flows inshore through Farm 1, while there are weak flows at Farms 5 and 6. July 2010 shows a stronger flow starting from the shore and moving offshore, west of Farm 1, as part of a counter-clockwise eddy sited offshore. November 2010 shows strong westward flows over most near shore regions.

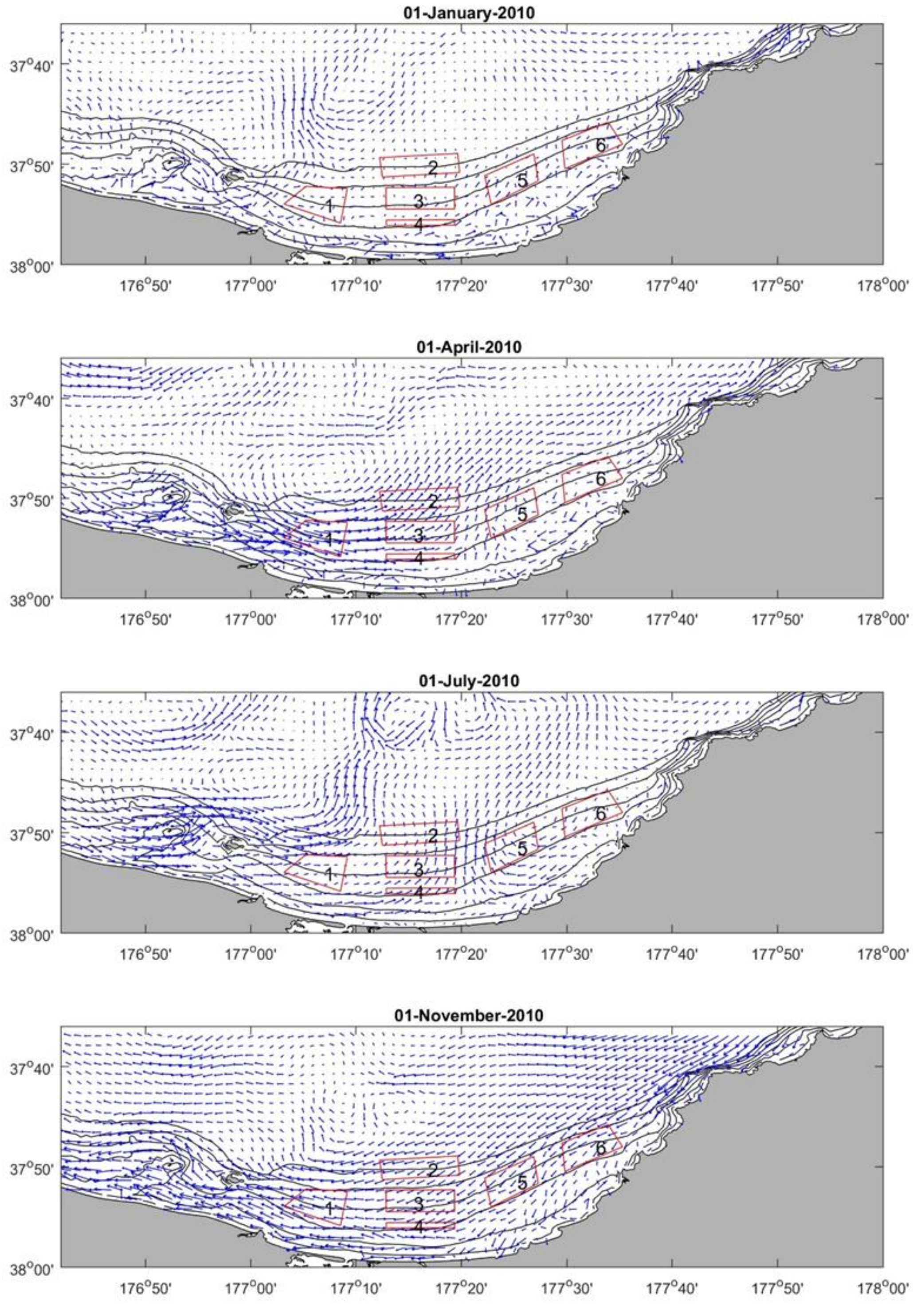

Figure 3. Examples of modelled currents illustrating the variability and complexity of flows in eastern Bay of Plenty. Depth-averaged currents showing direction and relative magnitudes for every second grid point in the model. Potential farm locations are also shown as numbered boxes (i.e. Farms 1 to 6).

Despite showing the horizontal complexity in flows, the depth-integrated model does have limitations as it is not able to resolve vertical flows, or differences in horizontal flows between surface and deep waters. Given that stratification of the water column has been noted, particularly in summer months (e.g. Longdill 2008), it seems likely surface wind-driven currents could at times be quite different to deeper currents.

The flow regime at an aquaculture site has implications for the management of benthic effects. An analysis of the currents from the model highlights the relatively low mean current speeds in the region (Table 3). Mean current speeds would be considered ‘weak’ or ‘very weak’ according to the shellfish aquaculture scale provided by Inglis et al. (2000). Under the Marlborough best management practice (BMP) benthic guidelines for salmon farming (MPI 2015b), mean mid-water current speeds of < 10 cm/s are termed ‘low flow’. Consequently, any development of both shellfish or finfish aquaculture will probably need to consider low-intensity approaches to culture to minimise benthic effects.

In terms of shellfish aquaculture, ‘low-intensity’ for offshore aquaculture, such as the sites presented here, is typically associated with a line spacing of about 50 m between longline structures. Inshore mussel farming would typically have a 10 m spacing, even in areas with relatively low flow. However, inshore farms are relatively small (i.e. < 10 ha) when compared to the large offshore areas considered here, and consequently their effects may also be small despite their relative intensity.

Low intensity farming is specified for the existing Eastern Sea Farms (ESL) site. Initially ‘very low’ intensity (100m spacing) will be established for a trial farm, and this will eventually increase to a planned 50m spacing. This seems appropriate for mussel aquaculture given the relatively low current flows in the region and the modelling work that had been undertaken previously. Given that there is a growing body of information of effects from low intensity offshore farms, it may also be possible to consider higher intensity farming. For instance, in some locations it may be preferable to have slightly larger effects from more intensive aquaculture, if a smaller area is impacted. Similarly, initial staging of very low intensity trial farms may now not be necessary, given the availability of additional information on effects from other sites (e.g. Wilsons Bay and Tasman Bay sites).

In the case of finfish farming, if it were considered, similar low intensity farming would also be required to mitigate effects of bio-deposition to the seabed, particularly if Marlborough BMP guidelines were followed (MPI 2015b). However, given the open ocean location considered here, oscillating wave-induced currents also have the potential to re-suspend deposits, which can then be moved by tidal and wind-driven currents. This has not be explicitly considered in the Marlborough BMP guidelines (MPI 2015b) and this wave action may act to mitigate seabed effects by enabling wider distribution of biodeposits, as is seen for shellfish farms (Giles et al. 2009). It may also be relevant to consider the effect of waves in this offshore, swell-dominated environment. Information on the wave environment in the Bay is presented in Section 2.2.

Table 3. Modelled depth-averaged current statistics showing mean and 99th percentile and maximum modelled currents in the centres of potential farm regions considered here.

Location	Mean Speed	99% Percentile	Maximum Speed
Farm 1	7 cm/s	31 cm/s	42 cm/s
Farm 2	5 cm/s	20 cm/s	40 cm/s
Farm 3	4 cm/s	17 cm/s	40 cm/s
Farm 4	5 cm/s	18 cm/s	34 cm/s
Farm 5	5 cm/s	15 cm/s	37 cm/s
Farm 6	4 cm/s	15 cm/s	42 cm/s

2.2. Waves

Wave-generated currents, from short period or swell waves, can play a critical role in the dispersal and resuspension of aquaculture discharges in areas where barotropic (e.g. tidal) and oceanic currents are too weak to provide significant dispersal (e.g. Panchang et al. 1997). These wave events may also affect site access and, therefore, the viability of an offshore aquaculture venture.

In order to assess the long-term wave climate in the region near Opotiki, a 30-year wave hindcast was provided by MetOcean Solutions Ltd (MSL). The location of the wave hindcast corresponds to the centre of the existing ESL farm (Farm 3 in Figure 2) and shows that significant wave heights[1] are less than 3 m for 99% of the time, with waves mainly coming from the northeast, i.e. traveling towards the southwest (Figure 4).

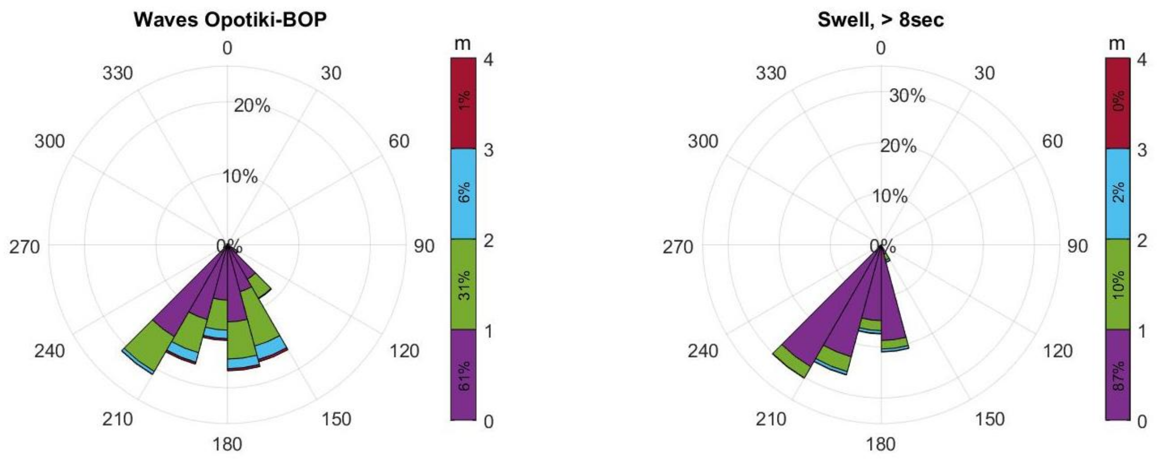

Figure 4. Wave directional “rose” information, showing significant wave height and direction (going to) information for the highest third of waves (left) and swell waves (waves with > 8s-period; right). The data provided by MetOcean Solutions is for a location at the centre of the existing consented ESL farm in the Bay of Plenty.

[1] Significant wave height refers to the mean height of the highest third of waves.

In terms of dispersing wastes from aquaculture, the period (and wavelength) of the waves is critical, with long period (and wavelength) waves able to have a greater effect on seabed currents. For instance a 8 s period wave of 2 m height can induce a 6 cm/s current at 50 m depth, whereas a 12 s period wave can induce currents up to 23 cm/s at the same depth. Strong episodic currents (e.g. >10 cm/s) near the seabed have the ability to resuspend waste material and distribute it to reduce the impact of benthic organic enrichment under the farms (e.g. Giles et al. 2009). As well as the size of the waves, the depth can also affect size of benthic currents, with shallower sites more likely to have higher wave-induced currents. This suggests that inshore sites could potentially be more dispersive than deeper offshore sites. There is little information available the effect of waves for aquaculture in New Zealand, consequently this would potentially need to be informed by monitoring.

The process of sediment redistribution includes a period in which suspended fine sediments could have short-lived, but potentially negative effects on benthic biota (e.g. Stevens 1987). Consequently, baseline data collection should consider monitoring turbidity to determine the frequency and magnitude of elevated benthic turbidity events in the existing environment.

2.3. Temperature

Temperature ranges can be very important for assessing the suitability of aquaculture species to be farmed. For example, Chinook (or king) salmon (*Oncorhynchus tshawytscha*) farming is typically situated in areas where the maximum water temperature remains below 18°C.

Greig et al. (1988) presented details of the seasonal variability of temperatures at a number of locations around the New Zealand coast. Data from Tauranga reveal that the temperature ranges from minimum winter surface water temperatures of around 13°C to maximum summer temperatures of around 24°C. Observations near Opotiki showed a similar variation, as did broader observations of sea surface temperatures (SST) within the Bay of Plenty by Park and Longdill (2006).

Heasman et al. (2009) presented the results from a number of temperature loggers deployed throughout the water column at the ESL site (Farm 3 in Figure 2). Temperatures ranged from 14 to 22°C in surface waters (Figure 5). The water column stratification “strength” (the difference between the 5 m and the 30 m temperatures) ranging between zero and 4°C during the same period (Figure 5). The thermocline depth (the depth where any observed strong temperature change occurs) was around 10 to 25 m (Figure 6).

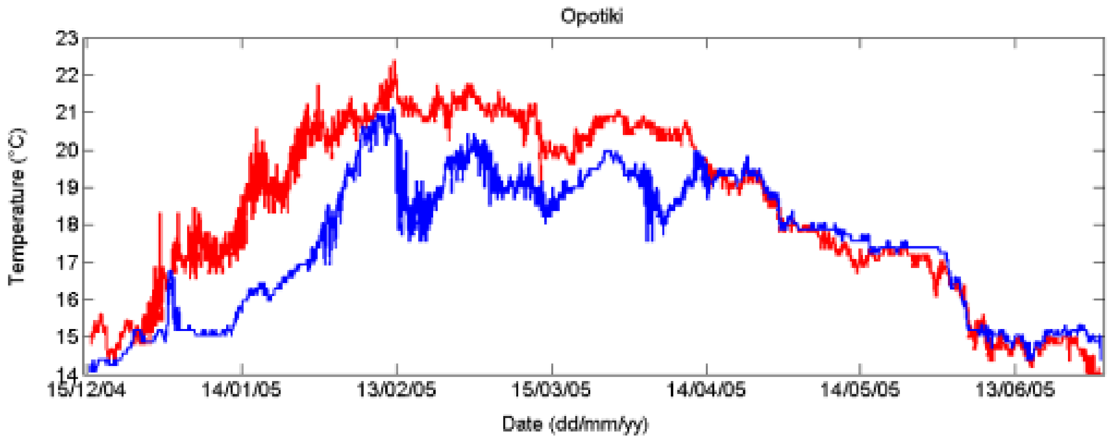

Figure 5. Surface (red) and bottom (blue) temperature logger temperatures from the Opotiki sites, showing similar temperature and stratification profiles over the measured 2004 - 2005 period.

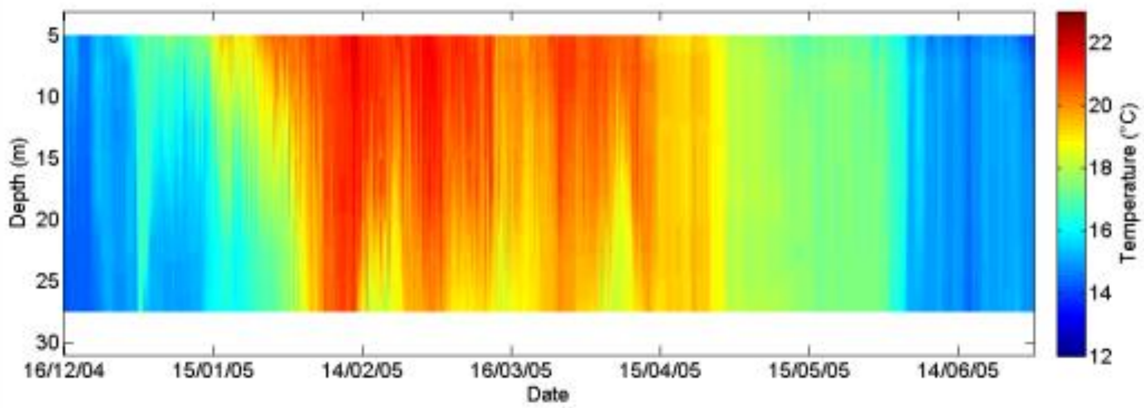

Figure 6. Temperatures measured with depth by HOBO temperature loggers near the Eastern Seafarms Ltd. site deployed over the period December 2004 to July 2005.

2.4. Summary of key physical characteristics

A summary of the key physical characteristics at an Opotiki research site was collated as part of work conducted by Heasman et al. (2009). These parameters are potentially important for species selection and the design of structures and vessels required to service the site (Table 4).

Overall, the physical characteristics of the area are such it is likely to be suitable for a range of aquaculture species, although notably, some cold water species (Chinook salmon) would not be suitable given that water temperatures range from 12–23 ºC. It appears the area would be considered 'low-flow' when compared to farming areas in the Marlborough Sounds. The wave climate is such that vessels will be able to operate in the area 80–94% of the time provided the vessels and structures are able to work in high wave and windy conditions. Wave-driven currents may also provide some mitigation for benthic enrichment effects.

Table 4. Summary of environmental parameters measured at a research site offshore from Opotiki between 2004 and 2008 (from Heasman et al. 2009).

Position:	**Opotiki**
NZMG-N, NZMG-E	6350681, 2883146
Depth range	28-40m
Waves *	Exposed, open ocean
Mean H_s / Peak Period (s)	1.7 m / 7.4 s
Max H_s / Peak Period (s)	6.5 m / 12 s
Max. steepness (H_s/Period)	0.65 (6.1 m/9.5 s)
Mean Yearly Access for vessels able to operate in up to 3 m swell	94%
Estimated mean yearly access for vessels able to operate in up to 2 m swell	80%
Largest swells from	*ENE* > N > W
Wind*	
Median speed	10 kts
Max speed (& direction)	45 kts (WSW)
Predominant direction	WSW
Estimated mean yearly access for vessels able to operate in 8 m/s (16 knot) winds	~ 95%
Currents	
Type	Dominated by ocean currents. Weak tidal component.
Strength	Moderate
Mean speed	7 $cm.s^{-1}$ (est)
Max speed	> 50 $cm.s^{-1}$ (surface)
Mean/net direction	~ 85° (west flowing)
Water temperature	
Mean surface temp (range)***	~17.4 (12.1–22.8)
Mean water column temp	17 ºC
Max water column temp	23 ºC
Min water column temp	12 ºC
Approximate period of stratification	January–April
Approximate thermocline depth****	10-25 m
Summer stratification strength****	3-4 ºC

* Wave data sourced from US National Oceanic & Atmospheric Administration (NOAA). WaveWatch III global models for Opotiki and are predictions for virtual buoys located nearest the site in question. This may be up to tens of kilometres from the actual location for the Wavewatch data.
** Wind data sourced for Whakatane Airport from NIWA CliFlo database for Opotiki.
*** SST data extracted from MODIS satellite images, note these data may differ from water column temperatures.
**** surface temperature – deep temperature

3. CARRYING CAPACITY

‘Carrying capacity’ is defined as a critical point at which the effects of aquaculture could have important effects on social, economic, ecological, cultural or aquaculture production indicators (see e.g. Inglis et al. 2000). Given the high-level nature of this report, we limit our discussion to production and ecological carrying capacity limits based on marine food availability for shellfish (i.e. seston). In determining carrying capacity limits we need to consider how a finite amount of particulate organic matter, some of which is able to regenerate (e.g. phytoplankton), can support an increasing amount of shellfish aquaculture. Feed-added aquaculture for fish will have a different carrying capacity and would require an assessment of biochemical interactions on a bay-wide scale; this is beyond the scope of this report.

Shellfish production carrying capacity is defined as the point at which increasing the amount of shellfish aquaculture could reduce the total aquaculture production of a region; whereas ecological carrying capacity is a level of culture at which other aspects of the ecosystem could be affected. Ecologically carrying capacity is typically much lower than the production carrying capacity (e.g. Jiang & Gibbs 2005), although it can be difficult to determine what constitutes a significant ecological effect. In considering such limits, we simplify our assessment and focus on the production carrying capacity for shellfish aquaculture.

3.1. Existing research (Longdill et al. 2006)

A substantial amount of information on potential effects from increased shellfish aquaculture (mussel farming) on phytoplankton depletion in the BOP has come from research by Dr Peter Longdill and colleagues for BOPRC (Longdill et al. 2006, Longdill 2008). The area considered in the work of Longdill et al. overlapped with, but was not the same as, the area considered here (Figure 7).

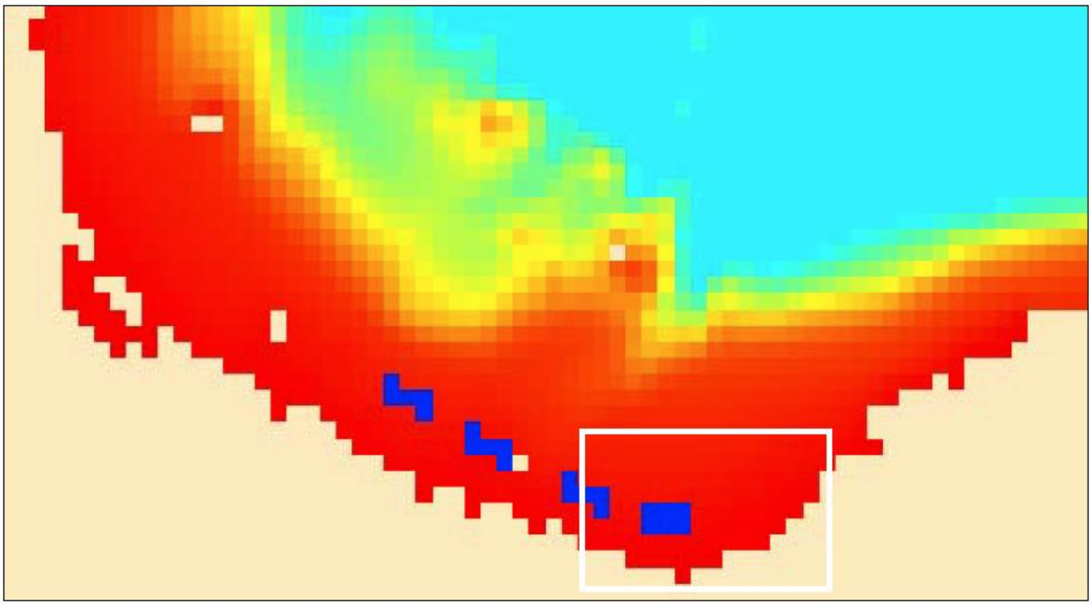

Figure 7. The four aquaculture areas considered in the modelling of Longdill et al. (2006) as indicated in dark blue. The eastern-most area includes the consented Eastern Seafarms site. The white box indicates the approximate area of interest of this report. Sourced from Longdill et al. (2006) with area of interest box added.

Some differences in the relative productivities of the areas considered by Longdill et al and the eastern region considered for this report are apparent. For instance, the phytoplankton modelling and remote-sensing analysis by Longdill et al. (2006) and Longdill (2008) appears to show the eastern area of the Bay of Plenty considered in this report has lower phytoplankton abundance (as indicated in estimates of chlorophyll-*a*) and productivity than the western areas (e.g. Figure 8). Coincident analysis of surface temperatures presented in Longdill (2008) shows this productivity is associated with cooler surface waters associated with upwelling to the west of Whakatane. For the purposes of our analysis, we consider the areas studied by Longdill et al. (2006) to be suitable for an initial estimate of potential phytoplankton effects in the region of interest considered here (e.g. Figure 1; Figure 7).

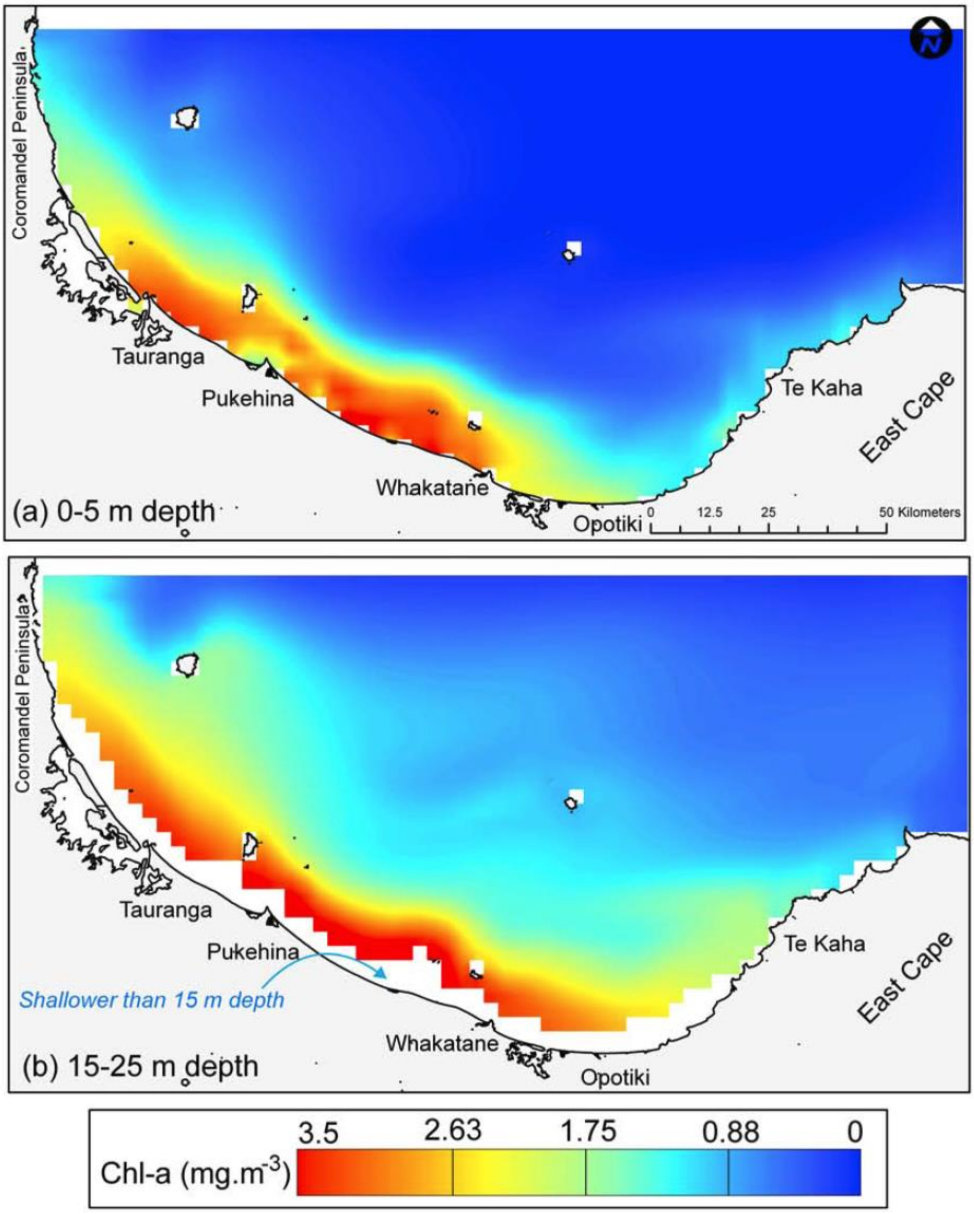

Figure 8. Modelled mean annual chlorophyll-*a* concentrations at 0-5 m (upper) and 15-25 m depths, from Longdill (2008).

Assuming that the modelled chlorophyll-*a* concentrations are accurate in the region (Figure 8), it appears that the concentrations would be in the range of 1 to 2 mg/m^3. This is a value that is considered to provide 'moderate' growing conditions for green-lipped mussels (*Perna canaliculus*, GLM) by Inglis et al. (2000).

The biogeochemical model used by Longdill et al. (2006) incorporates the interacting effects of hydrodynamics, oxygen, nutrients, phytoplankton, zooplankton and aquaculture in the region (Figure 9). This model is also referred to a as an nutrient-phytoplankton-zooplankton-detritus (NPZD) model.

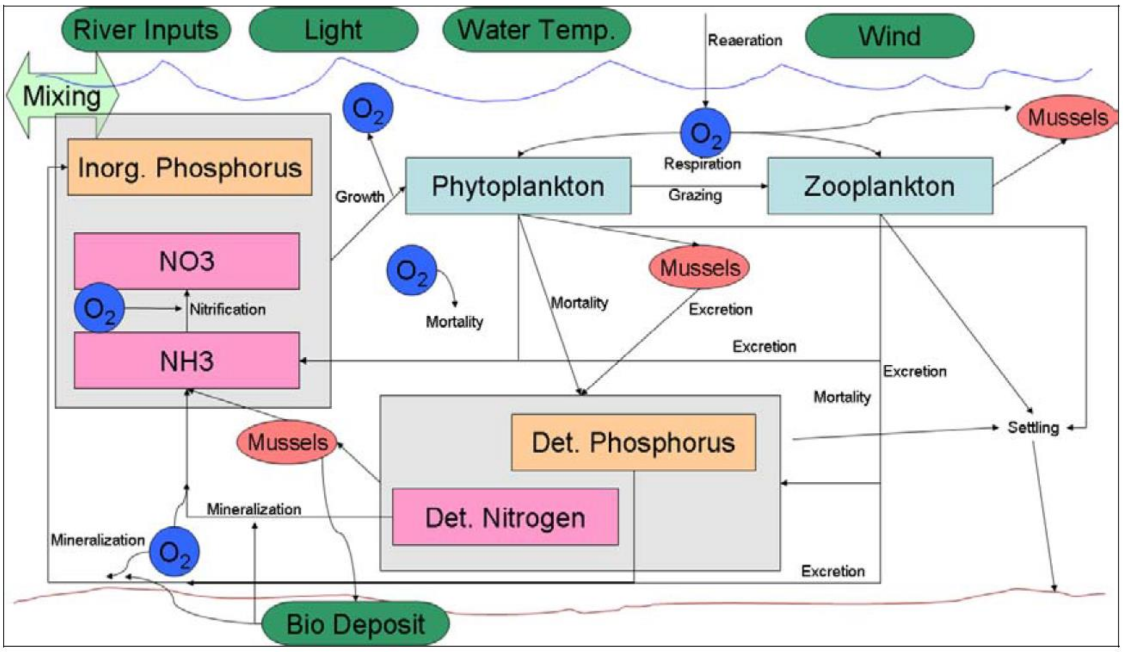

Figure 9. Schematic of modelled processes and fluxes used in biogeochemical model (diagram from Longdill 2008).

To repeat the development of this model is beyond the scope of this project. Consequently, we use the main findings of the Longdill et al. (2006) and Longdill (2008) model, in combination with other available data from the region, to consider:

1. a potential maximum carrying capacity for mussel farming in the region
2. an appropriate spacing to avoid large cumulative depletion of phytoplankton from overlapping effects of shellfish farms.

In applying the work of Longdill et al. (2006), we acknowledge that the locations, density of farming and species considered cannot be changed from the original modelling. That is, their work specifically relates to low density farming consented for the existing ESL site and only considers the culture of green-lipped mussels (*Perna canaliculus*, GLM). It is worth noting that among cultured shellfish species in New Zealand, GLM is likely to produce the highest filtration pressures, and consequently can likely be considered a worst-case shellfish species in terms of phytoplankton depletion and benthic effects (see e.g. Keeley et al. 2009; Forrest & Hopkins 2017).

3.2. Mitigation of cumulative depletion effects

Intensification around the existing ESL mussel farm would be expected to lead to an increase in phytoplankton depletion effects, either in the total area affected or in the magnitude of change. In order to assess the magnitude of cumulative effects from the development of multiple shellfish farms, Longdill et al. (2006) considered two and four-farm modelling scenarios. The total of 18,900 ha in Longdill's four-farm scenario was similar to that considered here (~15,900 ha plus the existing ~3,800 ha ESL site, i.e., a total of ~19,700 ha, Table 2).

The maximum levels of phytoplankton depletion outside farm areas under the largest four-farm scenario considered by Longdill et al. (2006) were similar to those of a two-farm scenario. This is despite the fact that in the four-farm scenario, a larger area was farmed (Figure 10). Using chlorophyll-*a* as a proxy for phytoplankton abundance, Longdill et al. (2006) also conclude that maximum averaged depletions in their modelled scenarios are in the order of 4-8%. They also conclude 'Given the physical and biological characteristics of the Bay of Plenty area, relative to the predicted levels of impact presented here, it is also unlikely that the ecosystem carrying capacity will be adversely affected.'

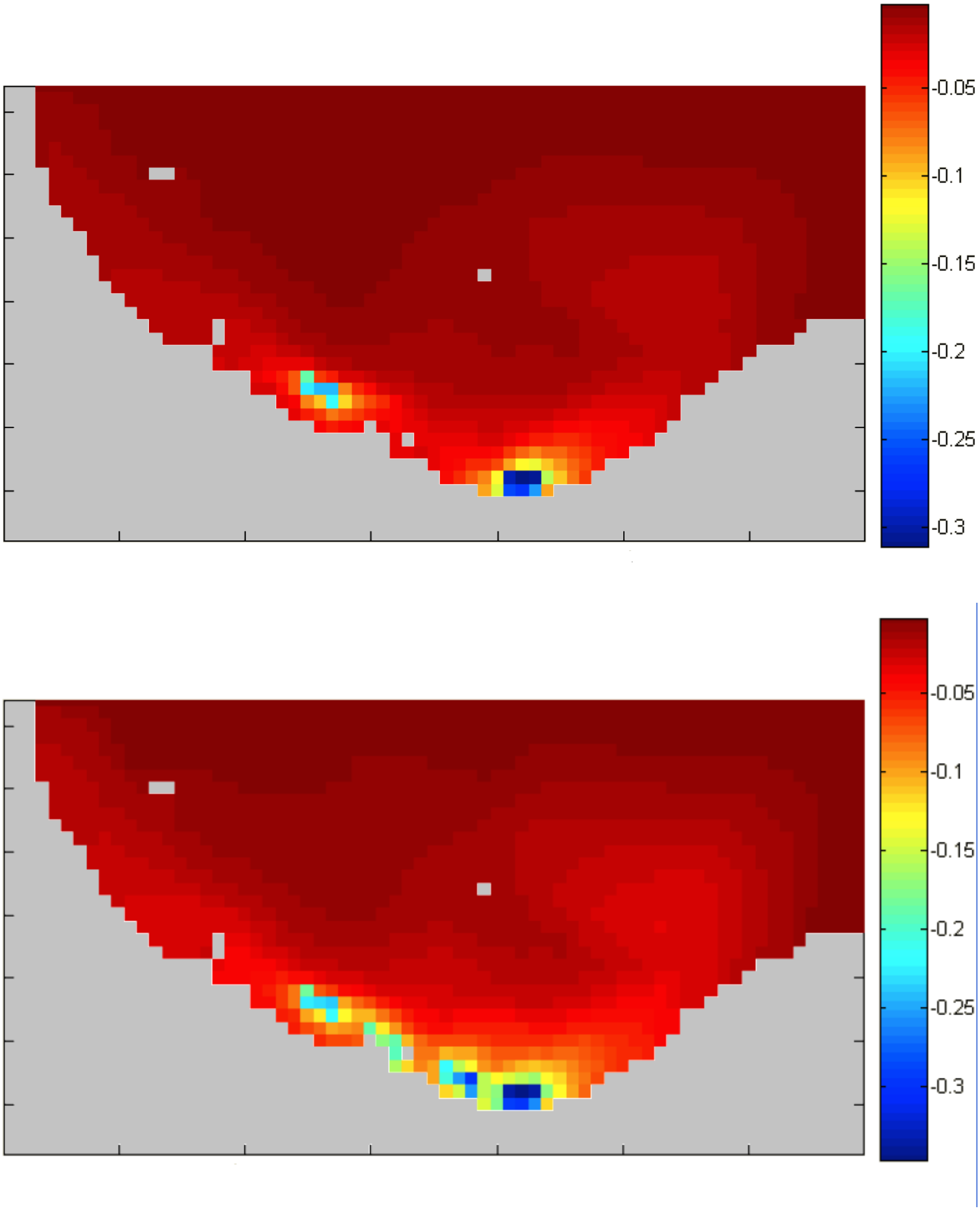

Figure 10. Chlorophyll-*a* concentration (a proxy for phytoplankton abundance) depletion modelled for the two (upper) and four-farm (lower) scenarios considered by Longdill et al. (2006). Note that units for the chlorophyll-*a* depletion colour scales are in mg chl-*a*/m^3 and are slightly different for each of the scenarios. Sourced from Longdill et al. (2006).

If similar phytoplankton depletion effects occur within the space considered in this report[2], it seems unlikely that the production carrying capacity of the region would be exceeded through GLM farming, provided it was undertaken at the low intensity considered in the modelling of Longdill et al (2006). However, it appears that reductions in chlorophyll-*a* concentrations of up to ~0.35 mg/m^3 are possible within the centre of the farmed areas (Figure 10). Consequently some reduction in the production of shellfish in the large areas is possible even under low-intensity farming.

The concept of ecological carrying capacity also suggests that ecological effects can occur at lower levels of farming intensity other than just determined by food availability. Even though Longdill et al (2006) do not predict an exceedance of ecological carrying capacity, they note:

> … Other factors that also impact on ecosystem health and warrant investigation are the significance of zooplankton mortality due to marine farms with respect to recruitment of other water-borne marine organisms and the potential impacts of mussel spat colonisation to new locations outside the marine farms (resulting to a decreased of marine biodiversity and/or community change).

Further limitations of the modelling (e.g. spatial resolution of the model, biological simplifications etc.) are also detailed in Longdill (2008)[3]. Consequently, based purely on the previous modelling work, we cannot state what an ecologically 'safe' carrying capacity for mussel culture would be. Nevertheless, the general findings from Longdill et al.'s work do provide a measure of confidence that, even at full development, ecological effects from low intensity mussel farming would be small.

However, both the modelling and remote sensing analysis presented in Longdill et al (2006) and Longdill (2008) also show that the eastern areas we have considered are potentially lower in chlorophyll-*a* (i.e. productivity) than the regions they had assessed. Consequently, our assumption that the regions are comparable could result in an overestimate of the maximum area that could be 'safely' used for mussel farming.

Therefore, if consideration is given to the development of large areas, a staged approach would seem prudent, one that initially considers a small utilisation (e.g. 10-20%) of proposed areas, but could allow for future growth. Given the existing ESL farm has a similar staging process, basing staging in a similar manner for new shellfish aquaculture seems sensible.

It is also relevant that the carrying capacity considered here only considers shellfish (specifically GLM farming); whereas potentially a mix of species will be considered. If

[2] This report considers up to ~19,700 ha, whereas Longdill et al. considered a total of ~18,900 ha.
[3] In personal discussions with Dr Longdill, he noted that short timeframes prevented a full discussion of limitations in the 2006 report and he recommended the more considered work of his thesis (Longdill 2008).

a mix of finfish and shellfish aquaculture is considered, revisiting the pioneering modelling studies of Longdill et al. (2006) in this region with new models would be recommended.

3.2.1. Spacing of areas

In addition to providing valuable information on the potential cumulative effects of large-scale development in the area, the work of Longdill et al. (2006) also provides information on the distances of depletion effects around the large areas considered in their study. We used this information to consider an initial appropriate spacing between candidate aquaculture areas. Longdill et al. (2006) show that beyond about 3 km of the existing ESL farm, the reduction in chlorophyll-*a* is predicted to be small (reduces by c. 0.15 mg/m^3) (Figure 11). Consequently, in the scenarios considered in the following modelling section (Section 5), we spaced farms about 4–5 km apart in the longshore direction and slightly closer for the cross-shore spacing (Figure 2 and Figure 11).

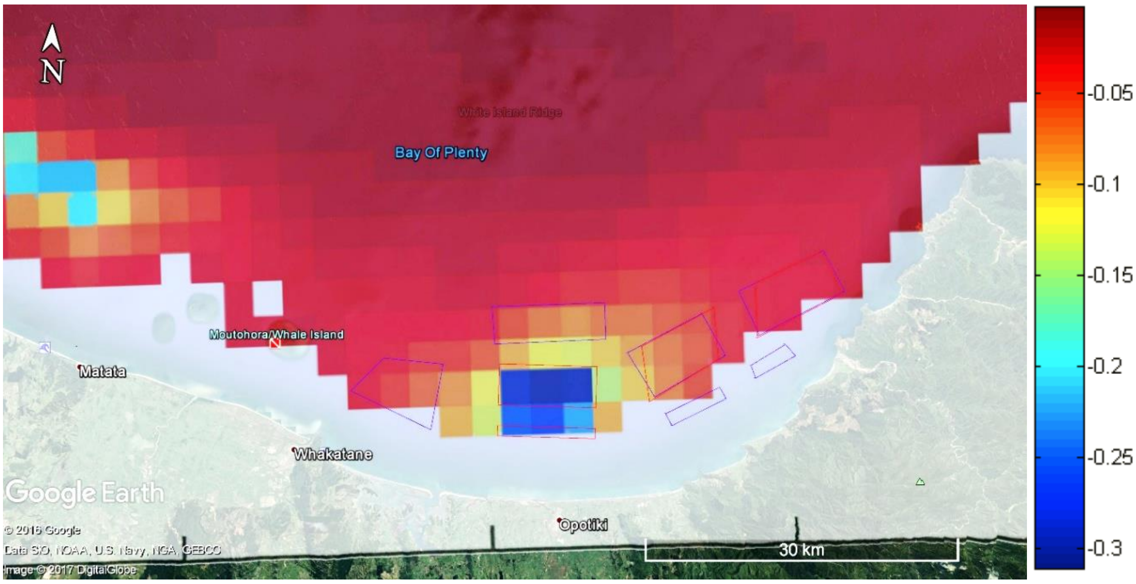

Figure 11. Potential chlorophyll-*a* depletion (in mg/m^3) over 15-25 m depth for a year from a two-farm scenario modelled by Longdill et al. (2006). Potential farm locations from this report (Figure 2) are superimposed on the depletion results of Longdill et al. (2006) to show that newly proposed sites fall outside of a 'depletion' halo' from a fully developed existing Opotiki farm . The farm scenario of Longdill et al. (2006) was larger (5,400 ha) than the existing Eastern Seafarm Ltd. site (3,800 ha). Another western mussel farm (4,500 ha) was also considered in this two-farm scenario.

4. PHYSICAL CONNECTIVITY MODELLING

It was identified that in order to assess and refine the locations of aquaculture areas in the region, that a study to estimate the physical connectivity between areas would be useful. This study aimed to determine physical connectivity in order to assess a range of potential aquaculture effects, including: biosecurity, mussel spat interception and phytoplankton recovery from depletion. In order to undertake this study we chose to use a particle tracking modelling approach.

4.1. Modelling approach

Particle tracking allows estimates of abiotic (e.g. sediment) and biotic (e.g. larval) transport and dispersion to be made. Particle tracking modelling traces the path of virtual particles released within an aquaculture area as they are moved by the estimated currents produced by a hydrodynamic model. The particles therefore describe the movement of neutrally buoyant material, or non-swimming organisms, which may be contained within parcels of water. Analysis of the path of thousands of virtual particles allows us to calculate the fraction of particles that will pass from one release area to another within a given timeframe. These statistics indicate the physical “connectivity” of farms, and can provide information relevant to issues such as the likelihood of invasive species moving between farms.

To undertake this work we used a particle tracking tool called ERCore[4], developed by MetOcean Solutions Ltd (MSL). Output from a hydrodynamic model was used to drive particles released within each of the farm areas. Modelled currents were supplied by MSL from an existing model of the Bay of Plenty, (for additional details see Appendix 1). The model is two-dimensional, has a regular grid horizontal spatial resolution of approximately 800 m, and includes the effects of winds and tides. The model provides depth-averaged currents and therefore does not allow for variation with depth. The two-dimensional current data were supplied as two-year hindcast results, spanning 2010 and 2011 at 1 hour intervals. Some of the results of this modelling are shown in Section 2.

The aim of this section was to estimate the horizontal physical connectivity between potential aquaculture areas and to use this to discuss the potential for biological connectivity. Given time constraints, this approach only considered passive connectivity, and did not include the effects of biological behaviour for the particles (e.g. swimming, or life cycle behaviours). The particle tracks were used to determine the fraction of those particles released at one farm which then passed through other farms within a given time interval. For each scenario, 70,000 particles were released at randomly chosen locations within a farm’s boundary at a rate of four particles per

[4] Technical details of this model are provided in a working manual of the document, which is available on request.

hour for the two year time period spanned by the hindcast. Particles were removed from the simulation 14 days after their release.

As noted earlier, initial model runs indicated that the north-west corners of farms 5 and 6 had greater connectivity with farms 1 to 3. Consequently, the shape of these farms was revised to the skewed red polygons ‘Version 2’ in Figure 2 (Section 1.1.1.). This alteration slightly reduced the physical connectivity between these farms. All results are shown for these skewed ‘Version 2’ farm shapes for Farms 5 and 6 (Figure 2).

4.1.1. Forward and backward releases

Particle releases in the model were used to estimate ‘forward’ physical connectivity between each farm and the other farms. Six tracking model runs were undertaken, one for each aquaculture area considered. These were then used to comment on passive movement of invasive species between farms. Six additional tracking model runs were carried out which went ‘backwards’ in time. These backwards runs show where particles arriving at a given farm came from, and were used to comment on the possibility of a farm receiving a reduced spat supply due to the placement of another farm. The fraction of particles arriving at one farm from another farm were similar in the forward and backward particle tracking. Thus we present outputs from the forward tracking model runs, with Appendix 2 giving summary results for the backward tracking modelling.

4.2. Results and discussions

Examples of particle tracks for releases from Farm 3 illustrate the diversity of currents between different months (Figure 12). While the long-term average currents in the Bay of Plenty are from west to east, within any particular month there are a wide variety of particle track patterns due to these currents.

The uppermost example in Figure 12 shows that particles released from Farm 3 travel mostly westward, while in the second example most particles travel only a short distance from their release location within Farm 3. The third example shows both eastward and westward movement, while the fourth example shows predominantly eastward movement of particles. While particle motion eastward from Farm 3 is predominantly along depth contours, particles moving eastward also typically move offshore as they travel (Figure 12). This offshore movement reduces the connectivity of Farm 3 with the eastern farms 5 and 6.

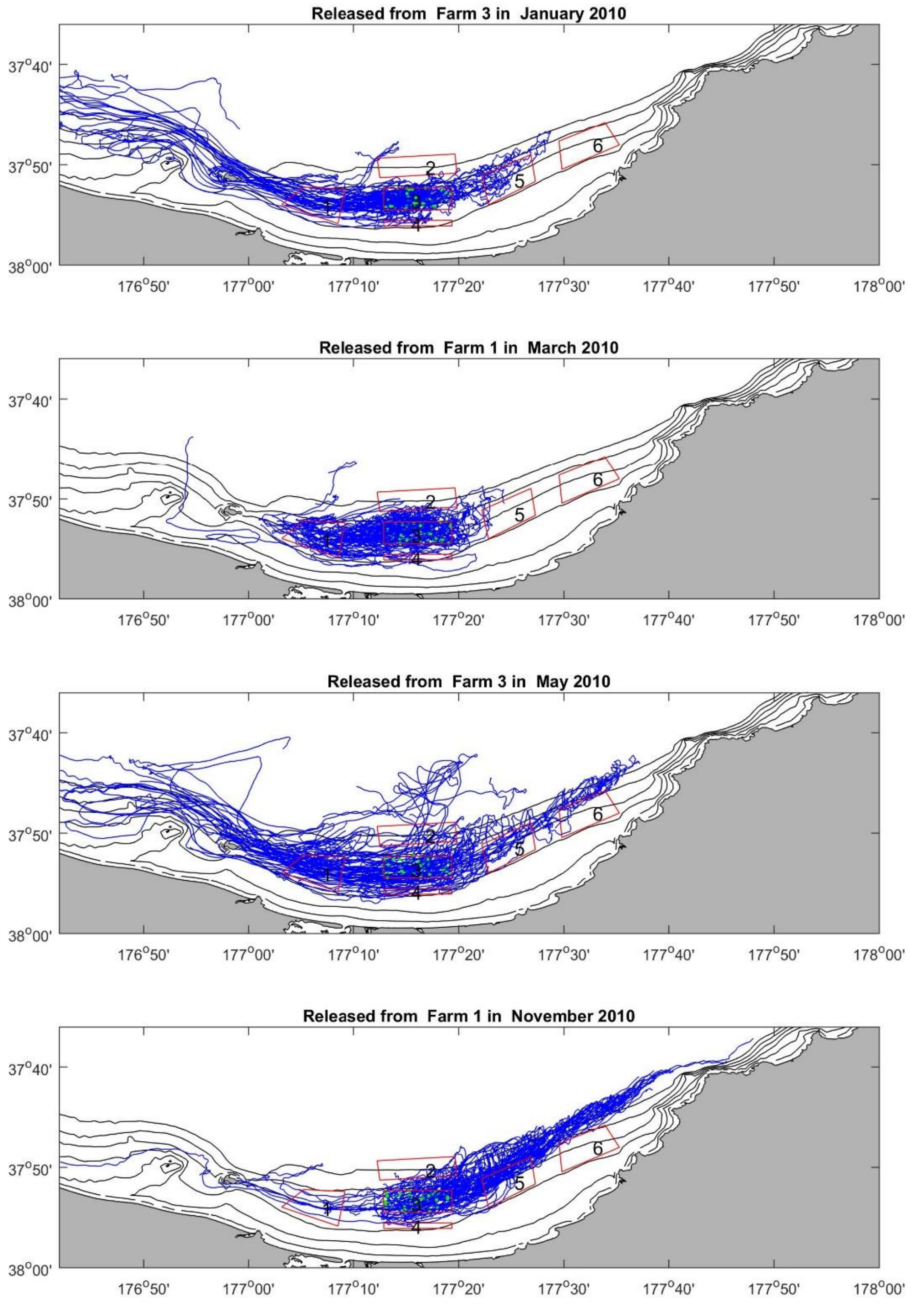

Figure 12. Examples of particle tracks from four months in 2010 from forward particle tracking. These illustrate the highly variable in currents within the Eastern Bay of Plenty depending on the month selected and the farm where they are released. Examples are for particles released at 12 hour intervals at random locations within Farm 1. Black lines show depth contours at 10 m intervals up to 60 m.

Examples of releases from Farm 1 are given in Figure 13. The upper two examples show significant westward movement and the third, the influence of an anti-clockwise eddy which is frequently present within the Bay of Plenty. This eddy takes particles farther offshore. The fourth example shows most particles spreading mostly eastward.

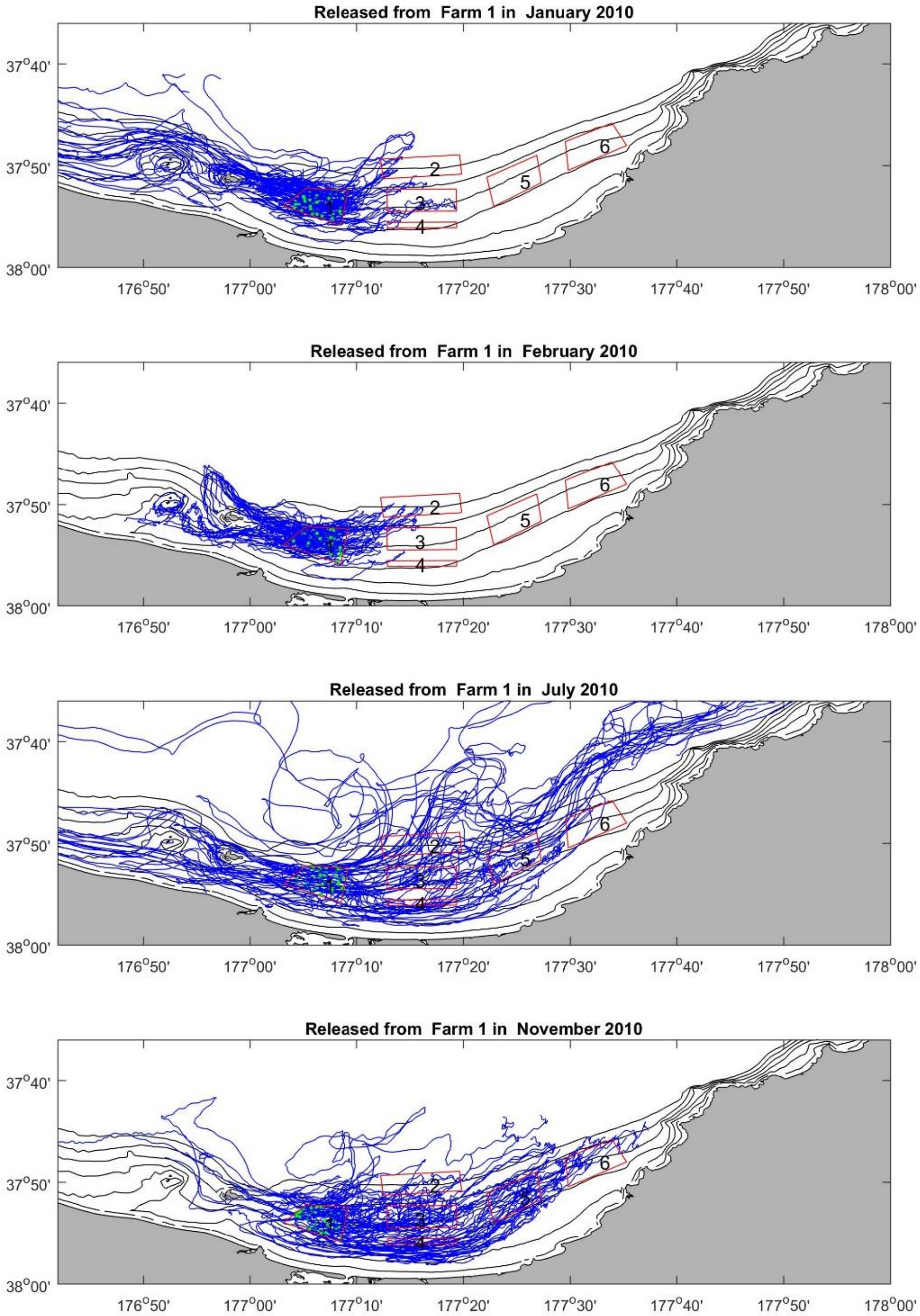

Figure 13. Examples of particle tracks from four months in 2010 from forward particle tracking. These illustrate the highly variable in currents within the Eastern Bay of Plenty depending on the month selected and the farm where they are released. Examples are for particles released at 12 hour intervals at random locations within Farm 1. Black lines show depth contours at 10 m intervals up to 60 m.

The examples of particle tracks presented for releases during particular months (Figure 12) are more relevant to this work than the long-term averaged currents (Figure 13). They demonstrate the variability in the currents between months and that, although the flow on average may be eastward, flows can frequently take particles westward, or offshore. Therefore potential new farm areas could be significantly influenced by other farms to their east within this time frame.

4.2.1. Particle connectivity results

The results of all releases from a given farm can be visualised as 'heat maps', where colour is used to indicate the numbers of particles that have travelled through a small area over the dispersal period (Figure 14). In the following maps, colours indicates how often particles are seen within each of the 800 m grid box of the hydrodynamic model after 1 day, 2 days, 5 days and 10 days. The colour scale has been arranged so that the grid boxes with the most particles are in dark red, with the lowest number of particles are indicated in blue. The dark red areas are concentrated around the farm area, where particles were being released. The colours of the heat map have been adjusted so that average number of particles for grid boxes which fall inside the releasing farm is set to be dark red for all examples shown. In addition, the colours are spaced on a log scale, as the number of particles falls rapidly with distance from the farm. Thus, the heat map colours visually exaggerate the extent of the area of covered by the particles, by overemphasising the small numbers of particles seen in the green and blue regions more distant from the releasing farm.

Figure 14 shows the results for particle releases from Farm 1. The white numbers below the farm number give the fraction of particles from the source farm arriving at the other farms within the given time frame. For example, only 0.09 (9%) of particles released from Farm 1 arrive at Farm 3 within 2 days, with 25% arriving within 10 days (Figure 14).

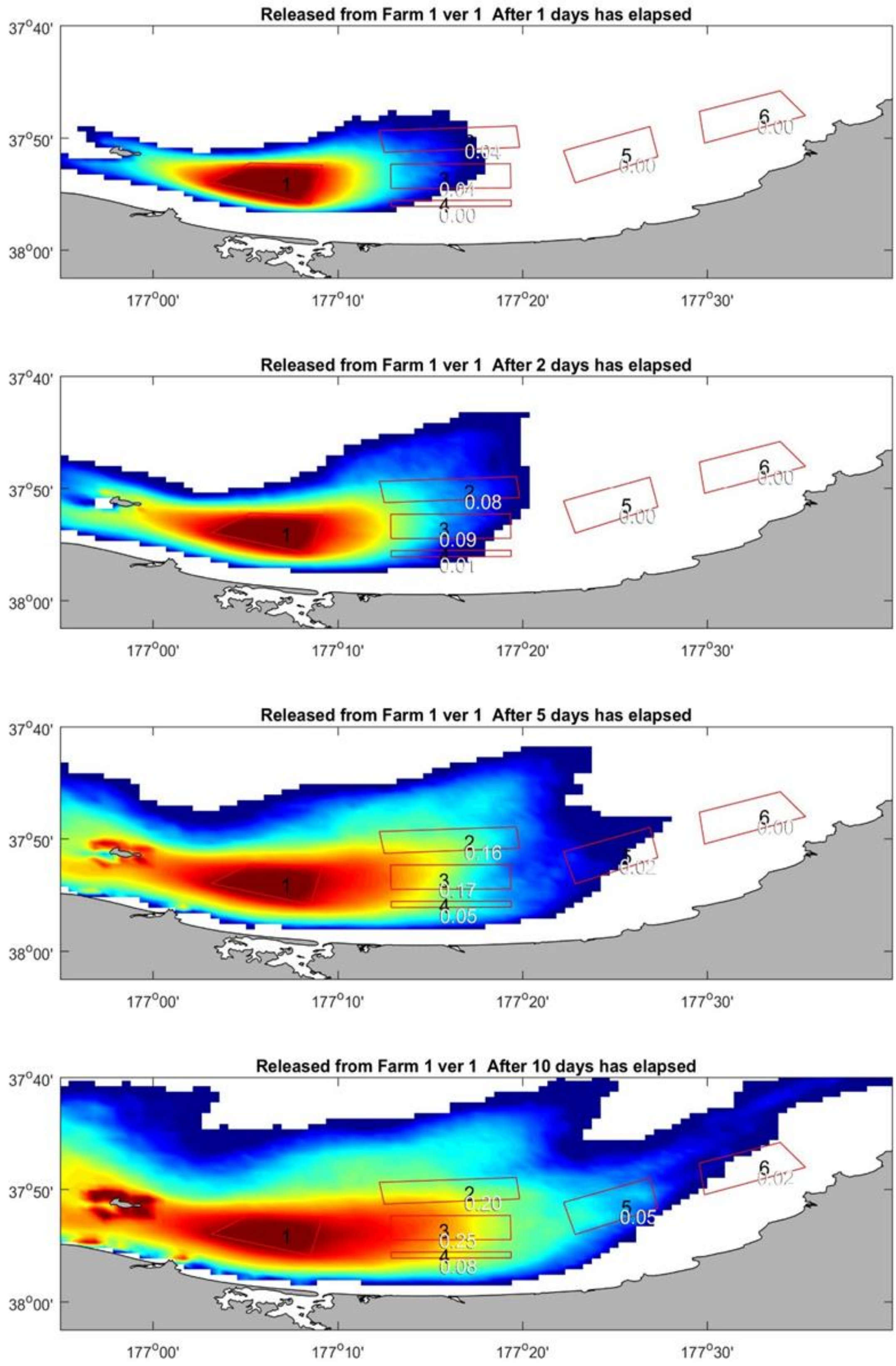

Figure 14. Heat map of observed particle locations after given time intervals after release from Farm 1. White numbers give fraction of released particles arriving at the other farms before the given time has elapsed.

Figure 15 shows how far particles have typically moved from their release point. This plot does not employ the logarithmic scale of the heat maps, and thus gives a more accurate impression of the extent of the area covered by significant numbers of the particles in the heat map. This figure shows the distance travelled in all directions from a farm, and therefore can't be used to estimate how long it takes to travel between farms.

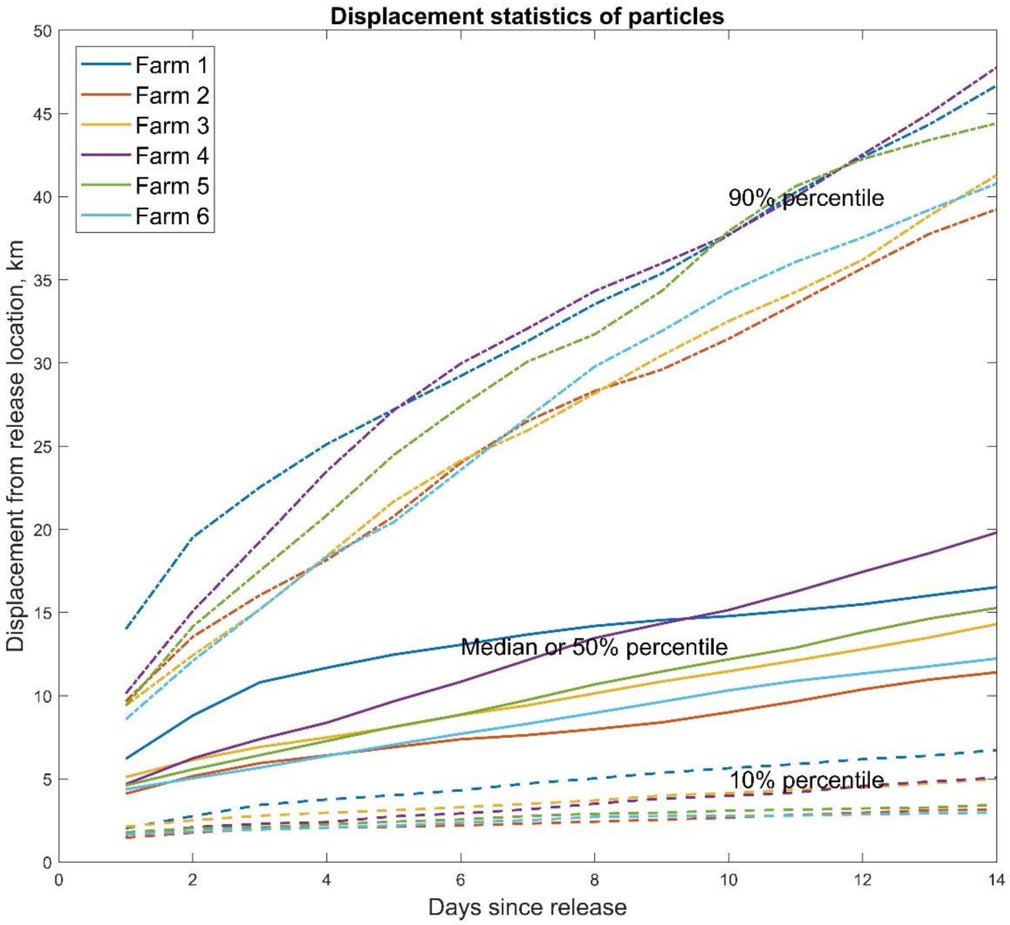

Figure 15. Displacements of particles (in kilometres) from their release point at 1-14 days after release. Colour indicates release location (i.e. farm number). 90% of particles were displaced by less distance than that described by the upper dashed lines. Middle solid lines describe median displacement. 10% of particles were displaced by less distance than that described by the lower dashed lines.

4.2.2. Connectivity statistics

The connectivity between each farm (particle source) and all other farms (receiving locations) is displayed in Figure 16. These plots describe the fraction of released particles that pass through another farm at 1–14 days after release, from forward particle tracking (i.e., this is the same type of information given by the white numbers in the heat maps in Figure 14, but here the values are available for all 14 days after release). For example, the upper left plot of Figure 16 shows that 10 days after they are released from Farm 1, 0.25 or 25% of the particles have passed through Farm 3, while 20% have passed through Farm 2.

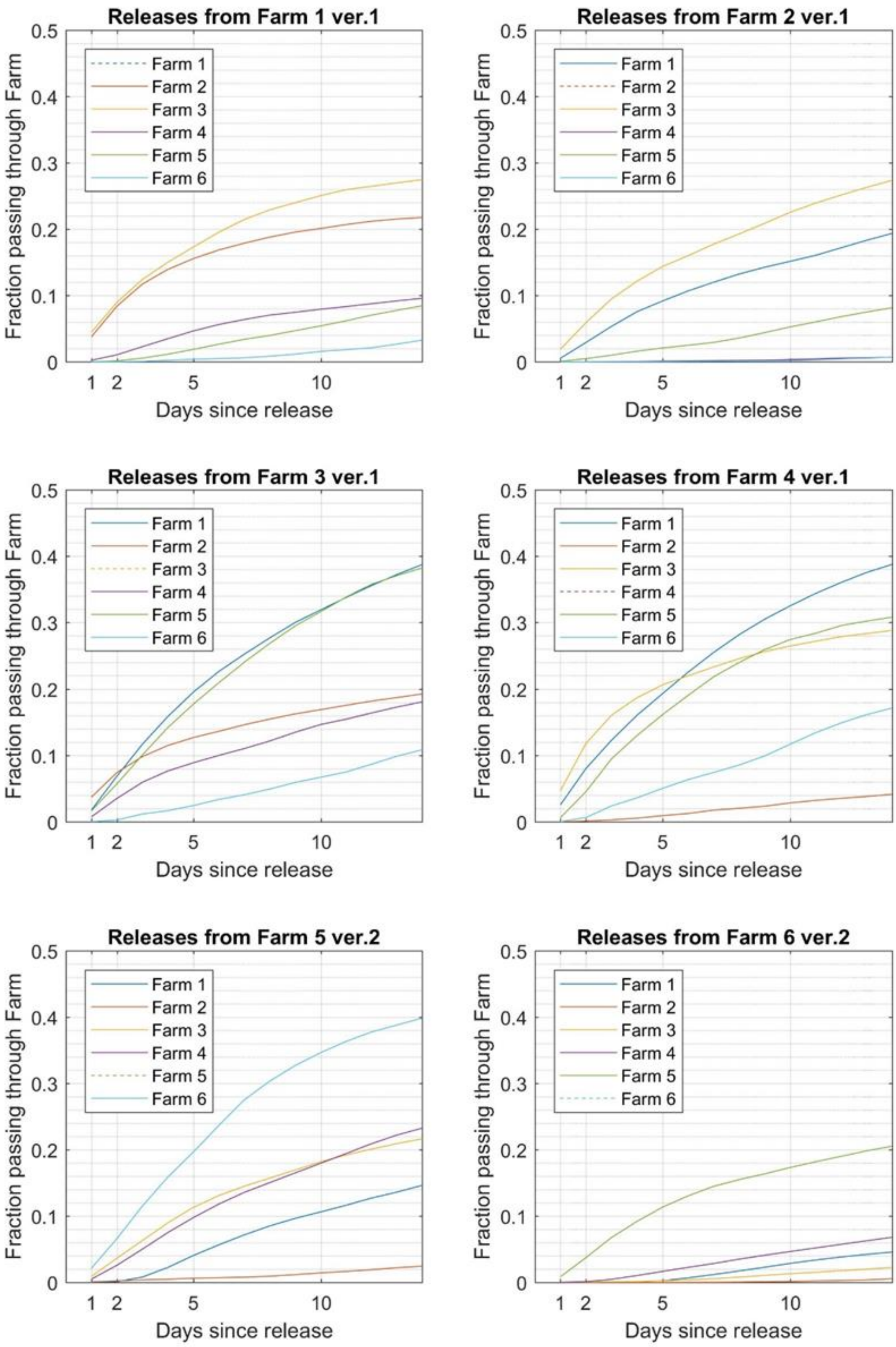

Figure 16. Curves show fraction of particles released from each farm arriving at other farms after given times in days. Legend shows colour of curve for farm where particles arrive. These graphs summarise all the forward particle tracking results.

Backward particle tracking was also undertaken and shows the fraction of particles arriving at a farm that have passed through another farm. Results were similar to Figure 16. The outputs from this work were numerous, as with other analyses of the particle tracking modelling. In order to provide succinct information, a few key results have been presented (see Appendix 2 for additional results of this modelling).

The analysis also demonstrated the insensitivity of the statistics in Figure 16 to within-farm location of particle release (Appendix 2). The choice of the horizontal eddy diffusivity coefficient, which simulates sub-hydrodynamic model grid scale mixing, similarly did not strongly influence the model outputs (Appendix 2). Estimates of how long particles released from one farm spend within another farm are also given in Appendix 2. These show that after 2 days particles have on average spent less than 0.5 days with another farm, while after 14 days have spent on average less than 2.5 days within another farm.

4.3. Relevance of physical particle tracking to aquaculture expansion

The overarching result of the particle tracking studies was that after two days there was less than a 10% connection between the modelled sites (the exception to this finding was that releases from the small Farm 4 showed more than 10 percent connectivity to the existing Farm 3). However, after 5 days this connectivity typically doubles, with values mostly below less than 20%; after 14 days, sites are typically about 30-40 percent connected. We briefly discuss these results in relation to the potential for effects on phytoplankton depletion, spat interception and biosecurity. Please refer to the relevant assessment sections for a more detailed discussion of these topics.

4.3.1. Phytoplankton depletion

A typical doubling time for phytoplankton is about two days. Thus if mussel farming reduced phytoplankton density by 50%, the farms are placed such that significant recovery in phytoplankton density would be expected between farmed areas within a two-day time frame. This result is consistent with the more comprehensive biogeochemical modelling of Longdill et al. (2006) in the Bay of Plenty, which shows depletion effects would be expected to be relatively small (< 0.2 mg chl-*a*/m^3) between areas (refer Figure 11 in Section 3.2.1). The particle tracking shows that the phytoplankton in 90% of water parcels would have more than two days to recover from any reduction in density due to grazing in one farm before they encounter another farm.

We also understand that species other than mussels may be considered for farming at the sites. If the alternative species are shellfish (or other filter feeders), we note that green-lipped mussels likely represent a ‘worst-case’ scenario in terms of phytoplankton depletion (Keeley et al. 2009; Forrest & Hopkins 2017). Consequently, our discussion here and the work of Longdill et al. (2006) are still relevant, although they could potentially overestimate effects from other filter-feeding species.

4.3.2. Mussel spat interception

Marine farming equipment, such as ropes and buoys, can provide surfaces which allow settlement of juvenile organisms, such as mussel spat. Some farm materials, such as spat catching rope, which has a very large surface area, may be particularly attractive to juvenile mussels that are ready to settle. Although a culture of shellfish can add to the supply of juveniles (if allowed to mature and spawn), new structures can also divert existing flows of spat away from established recipient populations.

At the existing ESL site, it is proposed that some of the area be used to catch mussel spat, which would have implications for the economic viability of that site given that mussel spat can be very valuable. Existing natural shellfish populations also require an ongoing supply of spat to ensure that young shellfish can replace shellfish that are lost to predation or natural mortality. Therefore, we broadly explore the potential effects on spat supply from the proposed development.

To estimate the effect of one farm on spat supply to another farm, we would ideally employ forward-tracking on particles (spat) released within known source regions and track them for 3-4 weeks (their typical larval duration, see e.g. Redfearn et al. 1986). We could then analyse the fraction of particles from a spat source that pass through one potential recipient farm (or settlement habitat) before arriving at the recipient farm of interest. However, little is known about which regions might supply spat to the farms, or about the amount of spat released from any source regions. Thus backward particle tracking was undertaken to estimate the proportion of those particles arriving at a given farm that have passed through another farm. The backward particle tracking thus gives an indication of how spat supply at one farm may be affected by another.

Given the larval duration of mussel spat is > 14 days and the backtracking connectivity statistics for proximate farms is up to ~40%, it seems likely that some interception by new farm structures is possible. That is, some spat that currently arrive at the existing farm could be intercepted by new farms. Our initial analysis suggests that, as with the particle tracking connectivity presented here, up to 40% of 'incoming' spat could pass through another farm within 14 days of arriving at the first farm. However, given that only a fraction of the spat will settle and any new mussel farm could also become a new source of spat, we consider that effects are likely to be smaller than the potential connectivity (i.e. 40%) modelled here.

4.3.3. Biosecurity

Our results suggest that short-dispersing pest organisms will have limited connectivity between the potential sites assessed here and that the potential for these species to spread is low. If there are organisms that have life stages that can survive for longer in the water column (e.g. 5-14 days), then there will be an increased chance they will be transported to surrounding farms. However, this does not mean that they will necessarily settle and grow in these areas. An increased separation of farmed areas can help to mitigate this issue; therefore, the inter-farm distances considered here should be considered as a minimum and should be increased if possible. Biosecurity implications are discussed in more detail in Section 5.

4.4. Limitations

The need to reduce the complexity inherent in natural systems when creating models means that any conclusions from the modelling need to be interpreted with care. In order to provide some measure of transparency, we briefly discuss the potential limitations of the modelling.

This particle tracking approach is limited to looking only at the two-dimensional physical connectivity between pairs of farms. Should more than one farm be developed, more work would be required to estimate the cumulative connectivity between multiple farms. In addition, as the model does not consider the effects of differential flows between the surface or the bottom of the water column. It is possible that these idealised particles will not be able to reproduce the extreme distances that could potentially be realised in the real environment. Nevertheless we consider the results useful for this sort of initial high-level assessment.

Phytoplankton depletion and recovery is extremely complex and while a two-day recovery provides a simple metric for estimating recovery, it does not consider the myriad of potential constraints that could also affect recovery of grazed phytoplankton populations. For example, nutrient availability, standing stock quantities and other grazing pressures (e.g. zooplankton) could all have an effect. However, the modelling undertaken by Longdill et al. (2006) does consider some of these factors.

While both our physical study and the earlier work of Longdill et al. (2006) have focused on phytoplankton depletion, it is also relevant that larvae, eggs or zooplankton can also potentially be grazed by GLM (e.g. Zeldis et al. 2004). These other organisms do not have the relatively short recovery of phytoplankton and could, therefore, be important when the considering wider ecological effects. It is outside of the scope of this work to address these issues, but important recreational, cultural or commercial species could potentially be affected (e.g. Gibbs 2004). Consequently, if large developments are permitted, updated modelling and ongoing monitoring, including of any species of concern, could be considered.

Larval forms of juvenile mussels also have the ability to swim, and while their swimming abilities maybe overwhelmed by horizontal currents in the region, they can regulate their vertical position to affect their net movement. Particle tracking models used in this report do not include such biological behaviour. Consequently, it is difficult to speculate as to the actual movements of spat in the region and our estimates need to be regarded with some caution. Although as mentioned previously, culture of GLM may also increase spat supply in the region.

Other biological factors, such as variation in the probability of settlement with age of spat/zooplankton, were also not included. GLM larvae are able to settle from about two weeks of age, therefore it is likely that spat caught at the existing farm is either sourced from distant populations (e.g. the Coromandel Peninsula or the East Cape). As mentioned previously, little is known about natural sources of GLM mussel spat in the region. This uncertainty in the source regions makes it difficult to accurately infer the potential for affects from the placement of new aquaculture areas.

The particle tracking has modelled physical particles without biological behaviour due to the short time frame of the project. However, even if behaviour was included in the model, there are still likely to be many unknowns; for example the probability of settlement with age for all species. Thus, interpreting the probabilities of these physical particles moving between farms requires a number of assumptions. The list below states some of the assumptions and gives an indication of how they may affect the probabilities of invasive species traveling between farms:

1. The particle tracking assumes a harmful marine organism (HMO) species is viable to settle from the moment of release, up until a duration limit with equal probability. (See Chapters 6 and 7 for further discussion on biosecurity and harmful algal blooms.) As with spat, this probability of HMO settlement changes with time and varies within populations. This changing probability has not been included in the modelling.
2. Not all particles leaving a farm with invasive species will have larvae; they may only be spawned at particular times of the year, or only be present in one part of an infected farm. Thus the probability of larvae arriving from another farm is likely much lower than the given probabilities for particles travelling between farms.
3. Some HMOs require male and females to settle in close proximity within a similar time, in order to establish a new population. Thus reducing the probability of successfully establishing a species in a new area.

4.5. Implications of changing area locations

This physical modelling has provided some useful initial metrics for considering the effects of initial candidate areas proposed for this report. We stress that areas presented in this report should not be considered to be fixed, and alteration of areas might occur for ecological, or other, reasons. As well as potential ecological concerns that could be associated with large areas, it has been suggested that smaller (e.g. < 2,000 ha) sites may be more attractive to potential investors than the four large (c. 3,700 ha) sites that are shown in our modelling (G. Coates, pers. comm., Aquaculture Direct). Consequently, future alterations of areas presented here might be considered.

For example, if a large amount of new area is considered (e.g. ~8,000 ha), this could be composed of two large (3,700 ha) sites, or four smaller areas (~2,000 ha) distributed within the larger areas considered here (Figure 2 [Section 1.1.1]). Distributing the areas across more sites would not have a large impact on our conclusions, provided the areas are located within the areas presented here and shellfish culture does not substantially exceed maximum GLM farming scenarios modelled by Longdill et al. (2006).

5. BIOSECURITY CONSIDERATIONS

5.1. Introduction

The term harmful marine organisms (HMOs) is commonly used to collectively describe marine pests, pathogens and parasites. HMOs have the capacity to negatively impact coastal ecosystems and associated resources and values. The interaction between aquaculture and HMOs is two-way; the industry is vulnerable to the negative effects of HMOs, yet at the same time can be a significant exacerbator of HMO risk. This section outlines the nature of those interactions, and provides a cursory discussion of potential implications in the context of Bay of Plenty (BOP) aquaculture development and marine farm site locations. Note that harmful algal bloom (HAB) species are also a category of HMO; however, HAB issues are considered separately in Section 6.

Impacts of HMOs on aquaculture

All of the main aquaculture sectors in New Zealand (green-lipped mussels, GLM; Pacific oysters; flat oysters; king salmon) have been negatively affected by HMOs to varying degrees. Floating subtidal systems (i.e. longline systems used for mussels, and sea-cage/pen finfish systems) are particularly vulnerable to adverse impacts from biofouling (Forrest et al. 2007; Adams et al. 2011; Woods et al. 2012). In shellfish aquaculture, for example, biofouling can impact all production stages, including the supply of juveniles (e.g. spat), crop grow-out, harvesting, processing and product marketing (Padilla et al. 2011; Fitridge et al. 2012; Forrest et al. 2014; Forrest & Atalah 2017). Biofouling can impact the quality, yield and value of the shellfish crop (e.g. via space and food competition, predation, shell erosion); impact infrastructure (e.g. through excessive weight and drag); impede industry processes such as harvesting (e.g. via physical interference); and lead to degraded product value. In a finfish context, biofouling be directly harmful to fish stocks (Atalah & Smith 2015), may harbour disease agents (Tan et al. 2002), or reduce water flow to the fish by occlusion of cage mesh apertures. The latter process can stress the fish (due to reduced dissolved oxygen), leading to degraded health and increased susceptibility to disease. Currently in New Zealand there are several biofouling species of concern to shellfish aquaculture (Forrest et al. 2014); among them the exotic fanworm *Sabella spallanzanii* and sea squirt *Styela clava*.

Disease can also be a significant issue in shellfish aquaculture. Although GLM have not to date experienced any significant diseases (Webb 2013; Castinel et al. 2014), the Pacific oyster and flat oyster sectors have been severely impacted. In 2010 the first outbreak of a Pacific oyster Ostreid herpesvirus-type 1 microvar (OsHV-1) in Northland led to dramatic production losses: between 90 and 100% of hatchery-produced Pacific oyster spat died after being deployed on grow-out farms, and up to 90% of natural spat was lost from culture sticks (Castinel et al. 2015). More recently in 2015, a fledgling, yet potentially high-value flat oyster (aka ‘Bluff oyster’) aquaculture industry in Marlborough was decimated by an exotic parasite *Bonamia ostreae* (Lane et al. 2016).The occurrence of this species in Marlborough led to severe restrictions being put in place to try and contain *Bonamia's* spread and impacts (MPI 2016; OIE 2016). More recently, *Bonamia ostreae* was recorded on two farms in Big Glory Bay, Stewart Island. MPI made the decision to require farmers to remove all flat oyster stocks from Big Glory Bay and Marlborough, to reduce the risk of the parasite's spread to the iconic wild Bluff oyster fishery (see: https://www.mpi.govt.nz/document-vault/18701).

Role of aquaculture in the spread of HMOs

Historically, aquaculture seed-stock movements among countries have been responsible for the spread of many HMOs globally (Minchin 2007). In New Zealand, any such international movements would be controlled by stringent border standards. However, domestic aquaculture activities are an important contributor to the regional and inter-regional spread of HMOs (Castinel et al. 2015; Forrest & Fletcher 2015; Castinel & Hopkins 2016), which can exacerbate risks to the industry itself and to the wider environment. In particular:

- As many HMOs have a limited natural dispersal capacity, regional or inter-regional movements of aquaculture vessels, equipment and stock (e.g. shellfish seed-stock, finfish juveniles) infected by HMOs can lead to the inadvertent spread of such organisms. Such risks form part of a broader context of biosecurity risk that arises from other human activities, in particular the movements of vessels of all types (e.g. recreational boats, barges, fishing boats, ships) to, and within, New Zealand (Dodgshun et al. 2007; Hayden et al. 2009; Hopkins & Forrest 2010; Inglis et al. 2010).
- Marine farms provide an extensive surface area of artificial structure, which provides habitat for many organisms, including certain HMOs (Cook et al. 2006; Woods et al. 2012; Atalah et al. 2016). As some HMOs can become abundant on marine farms, such structures can provide a reservoir from which HMOs can spread among marine farms or to the wider environment (Hunt et al. 2009; Forrest et al. 2013; Forrest & Hopkins 2013; James & Shears 2016).

We have not undertaken an extensive search for records of existing harmful marine organisms (HMOs) in the BOP region and, as such, the information below should be treated as preliminary. Regionally, the BOP appears to be relatively unimpacted from the perspective of coastal development and habitat modification, with the main exception being the port of Tauranga. A biological baseline survey in Tauranga Harbour in 2002 revealed a total of 316 species or higher taxa. Among these, 12 non-indigenous species (NIS) were identified, along with 202 native species, 40 cryptogenic species (those whose geographic origins are uncertain) and 62 species indeterminata (taxa for which there is insufficient information to enable identification to species level) (Inglis et al. 2006). At the time of that survey, none of the 12 NIS were species on New Zealand's register of unwanted marine organisms. Subsequently, however, at least three organisms formally identified as marine pests

(MPI 2015a) have been recorded from Tauranga. These are the Mediterranean fanworm *Sabella spallanzanii*, the Asian kelp *Undaria pinnatifida*, and the clubbed tunicate (sea squirt) *Styela clava*. In the wider region, the 'marine biosecurity porthole' website administered by MPI (see: http://www.marinebiosecurity.org.nz/) also shows records for the Asian paddle crab *Charybdis japonica* (a designated marine pest) in northeast Coromandel (Whangapoua Harbour), while the sea squirt *Didemnum vexillum* (a pest of interest, but with no designated status) has been described in Tauranga and also Whangamata (Kott 2002).

Further enquiries (e.g. with BOPRC) may reveal more information on HMOs to the east of Tauranga, in the vicinity of the Opotiki marine farm development area. Due to the absence of significant coastal development, it is certainly possible that HMOs do not yet occur in the area, although without systematic surveillance it may be the case that HMOs are present but have not been detected. We also note that pests of regional interest have been described from a preliminary survey of biofouling on the existing Opotiki mussel farm, conducted in 2012 by Atalah et al. (2016). At the time of their survey, the Opotiki farm had been in place for c. 5 years. The Atalah et al. study recorded only 19 biofouling taxa, including two regional aquaculture fouling pests described for the Firth of Thames (Heasman & de Zwart 2004; Jeffs & Stanley 2010); namely, the triangular barnacle *Balanus trigonus*, and the hydroid *Amphisbetia bispinosa* (aka 'mussel beard'). Of significance is that many of the fouling species that have been a periodic or regional nuisance to the New Zealand mussel industry were absent from Opotiki; in particular the sea squirts *Ciona intestinalis*, *Styela clava* and *Didemnum vexillum*, and the Asian kelp, *Undaria pinnatifida* (Woods et al. 2012). Atalah et al. (2016) attributed the absence of such species from Opotiki being due to: (i) their limited natural dispersal capacity, and (ii) the fact that Opotiki has been stocked from locally caught mussel spat and is relatively isolated in terms of vessel movements. As such, Atalah et al. suggested that newly established 'offshore' marine farms like Opotiki have the potential to be kept free of a range of problematic fouling organisms, provided the introduction of such species via human transport pathways can be mitigated.

The further development and intensification of marine farming in the Opotiki region, with the possibility of an adjacent coastal port development, raises the likelihood of an increased network of aquaculture and vessel movements. These movements will be: (i) from other parts of the country, potentially connecting this relatively isolated region to other localities where HMOs occur; and (ii) to and among marine farms, thereby connecting the farms themselves. For example, vessels may move to the region from other New Zealand ports (e.g. for farm development or ongoing operations) and farms may need to be stocked with juveniles sourced from other locations. As such, a comprehensive assessment of biosecurity implications will need to address a broad suite of issues and evaluate options for management. The risks in part depend on the actual species cultivated (Forrest & Hopkins 2017), hence the discussion below is only a very high-level assessment with respect to the issues that need to be considered, and the possible spatial configuration of the farms.

5.2. Key biosecurity considerations

Understanding and mitigating risk pathways from outside the Opotiki region provides the best defence against the establishment of new HMOs. This process could be based on principles for marine pest risk pathway management described by Forrest et al. (2009). Experience in New Zealand and globally indicates that managing HMOs after they have established new populations in coastal habitats is difficult, expensive and seldom successful (Hunt et al. 2009; Forrest & Hopkins 2013; Castinel et al. 2015). However, the Opotiki development provides a unique situation, with ‘offshore’ farms relatively isolated from coastal source populations of HMOs. Thus opportunities may exist for management in terms of both preventing establishment of HMOs, and also for eradicating or controlling any that do become established.

5.2.1. Understanding and mitigating risk pathways from outside the region

The external pathways for the introduction of HMOs to aquaculture development areas are typically varied and, with respect to aquaculture activities themselves, depend on the required farm infrastructure and the species farmed. Key considerations are likely to include:

- Risks from specialist vessels used to set up farms. For instance, installation of anchors to hold mussel farm ‘backbone’ lines in place, and to anchor finfish cages, often relies on specialist vessels and dive crews from Marlborough and Nelson. These source regions have a range of high-profile marine pests hence, without management, movements of these vessels to Opotiki could provide a high-risk pathway for HMO introduction.
- Sources of equipment used to set up and maintain marine farm structures (e.g. ropes, floats, baskets, fish cages). If second-hand equipment is acquired from outside the region, transfers of HMOs via biofouling, or via entrained water and sediment, are risks that need to be addressed by appropriate pathway treatments (Forrest et al. 2011).
- Sources of juveniles used to stock farms. Of particular interest is the movement of shellfish spat and seed acquired from wild sources (i.e. not from hatchery production). Wild caught spat and seed-stock are exposed to biofouling and potentially to disease, therefore such transfers represent a potential high-risk pathway. The potential for disease introduction needs specific consideration, especially for those species already known to be susceptible to significant pathogens or parasites (e.g. Pacific and flat oysters, respectively).

The risks from these pathways, and decisions regarding the efficacy of mitigation, depends on the broader biosecurity context. For example, aquaculture structures often attract fish (Gibbs 2004; Morrisey et al. 2006), and therefore recreational boaters (Forrest & Hopkins 2017). Recreational boats in New Zealand are recognised as a significant contributor to biosecurity risk (Floerl et al. 2005; Acosta & Forrest 2009; Brine et al. 2013; Forrest 2014). To make management of Opotiki aquaculture pathways worthwhile, it will be important to ensure that recreational and other non-aquaculture risk pathways are equally managed, so that any industry management efforts are not undermined.

5.2.2. Mitigating the risks from HMOs that become established

Arguably the two most likely scenarios for the establishment of new HMOs in the Opotiki region are as follows:

- HMOs establish in coastal port/harbour areas that already exist, or are developed to support aquaculture industry growth (e.g. vessel moorings and berths). The most likely scenario would be the introduction of new HMOs as a result of vessel movements from other New Zealand ports.
- The establishment of HMOs on marine farm structures, and subsequent spread. The most likely scenario would be the direct introduction of an HMO to a farm site via infected vessels or equipment (from within or outside the BOP region), with the subsequent 'reservoir' effect of the infected farm leading to spread to other farms and/or the wider environment.

Several general approaches exist to mitigate risk in the event that HMOs become established. A comprehensive assessment will be needed to evaluate options based on situation-specific risks; most such risks cannot be assessed until operational details are known. However, one of the issues for which some assessment can be made at this early stage relates to the potential for any introduced HMOs to spread among farms and/or to the wider environment. The related question is whether marine farm sites can be located in a way that minimises such eventualities.

Conceptually, the ideal approach to prevent the spread of HMOs between farms would be to arrange them as a few, large, sites (e.g. 2–3 large sites), each positioned so that their connectivity by natural dispersal processes was minimised. This approach would involve operating each farm as an independent management unit (IMU). Where natural connectivity is low, and effective pathway management measures can be implemented (e.g. no sharing of equipment, vessels and spat/stock among IMUs), an HMO incursion at one farm site has the potential to be contained.

From an aquaculture management perspective, the IMU concept means having farm sites as far apart as is operationally feasible along the main axis of modelled long-shore water movement (e.g. farms 1 and 6 in Figure 2), and/or staggering their

arrangement perpendicular to the main current axis (i.e. from nearshore to offshore; such as farms 2 and 4). However, note that ecological risk must also be accounted for in the spatial arrangement of IMUs. For example, it is important to ensure that the approach does not result in farms being placed in locations where they are highly connectivity with sensitive natural habitats (e.g. rocky reefs).
In terms of theoretical site connectivity, the various particle tracking modelling scenarios from Figure 16 suggest that after 2 days of particle dispersion there is < 10% connection between the modelled sites. However, after 5 days this doubles to < 20%, and after 14 days, sites are 30-40% connected. Use of these results to determine whether IMUs may be feasible and effective from an ecological perspective (i.e. ignoring operational considerations) is reasonably complex. The particle tracking model simulates the dispersal of a passive particle among discrete locations, which is: (i) simplistic in a real-world context; and (ii) does not reflect the entirety of ways that natural processes may connect farm sites.

For example, whereas most marine HMOs naturally disperse via planktonic drift with water currents, the extent to which this occurs varies widely. All of the MPI-designated marine pests (MPI 2015a) have dispersal strategies that involve the release of planktonic propagules (e.g. animal larvae, seaweed spores) from reproductive adults. These planktonic life-stages can last from hours to weeks, depending on species (Table 5). In the case of pathogens and parasites, the risk organisms themselves may be capable of dispersal as planktonic organisms after release from a host; this can occur for the parasite *Bonamia ostreae* in the flat oyster, and the OsHV-1 virus in Pacific oysters. We would need to undertake a more in-depth assessment of available literature to gain a broader understanding of planktonic durations for known HMOs. Even then, however, it should be recognised that for many species (especially pathogens and parasites) detailed life-history information may not be available.

While the particle tracking approach highlights broad differences in potential connectivity based on propagule duration, model outputs potentially overstate the level of natural inter-farm connectivity that would occur in practice. Important factors that will affect actual inter-farm connectivity by planktonic propagules include: propagule depth in the water column; mortality due to factors such as predation; physical attributes of propagule release (e.g. seasonality, timing, magnitude); and biological attributes of the propagules themselves (e.g. changes in competency during planktonic advection). For example, the particle dispersion model does not incorporate a minimum period of planktonic development that is required by some HMOs (see Table 5) before they are competent to ‘settle’ (i.e. transform from their planktonic stage to a juvenile organism).

Table 5. Examples of marine pests that show a variety of dispersal strategies and habitat requirements. All are MPI-designated marine pests except blue mussels and *Didemnum vexillum*, which are of regional aquaculture significance in Marlborough.

Common name	Scientific name	Mechanisms of spread or establishment	Main habitats
Japanese kelp	*Undaria pinnatifida*	Spore dispersal: spread by spores likely limited to 10s or 100s of metres Drift of mature plants: unlikely to be important in deep soft-sediment habitats	Hard substrata; e.g. reef, artificial structures
Colonial sea squirt	*Didemnum vexillum*	Larval dispersal: c. 1 day in plankton Fragmentation may be important for local-scale dispersal	Hard substrata (based on NZ experience)
Clubbed sea squirt	*Styela clava*	Larval dispersal: c. 1 day in plankton	Hard substrata & soft-sediments
Mediterranean fanworm	*Sabella spallanzanii*	Larval dispersal: up to 2 weeks in plankton	Hard substrata & soft-sediments
Blue mussel	*Mytilus galloprovincialis*	Larval dispersal: up to 4 weeks in plankton, but larvae not competent to settle until c. 18-20 days	Hard substrata; e.g. reef, artificial structures
Northern Pacific seastar	*Asterias amurensis*	Larval dispersal: larvae competent to settle after c. 23-122 days. Migration of mobile adults may be possible.	Hard substrata & soft-sediments

A further consideration is that planktonic propagule dispersal may not be the only mechanism of natural spread. For sessile species (i.e. species that are attached to the substratum as adults), the release of planktonic propagules is often the only means of dispersal. However, mobile invertebrates like crabs and sea stars may also be able to move across the seabed and therefore between farms (e.g. have the ability to move up and down anchor warps), or from farms into natural habitats. As such, the spread of such species is not necessarily limited by constraints on the dispersal of planktonic larvae. The MPI marine pest list includes four mobile species, of which one (the crab, *Charybdis japonica*), is already established in the wider BOP region (see Section 5.1). It is not certain that this species poses a risk to suspended aquaculture; however, similar organisms do. For example, the indigenous decorator crab *Notomithrax minor* is considered by the Marlborough mussel industry as a significant predator of GLM spat (Forrest et al. 2014).

Finally, the analysis of inter-farm connectivity with the particle dispersion model does not account for the varying habitat requirements of HMOs. Assuming generally suitable environmental conditions in the Opotiki area (e.g. with respect to water temperature), seabed habitat requirements are a critical consideration for benthic HMOs. Species like the kelp *Undaria* and sea squirt *Didemnum* are primarily a threat on hard substratum habitats, such as marine farms and adjacent rocky reef. Their capacity to occupy soft-sediment habitats, such as in the vicinity of the Opotiki farm development, is likely to be minimal or non-existent. Accordingly, their spread among farms will rely solely on plankton propagule dispersal, or anthropogenic mechanisms. By contrast, most of the MPI-designated pests are habitat generalists. These include three crab species, the seastar *Asterias amurensis*, the fanworm *Sabella* and sea squirt *Styela*. All of these species are capable of inhabiting soft-sediment habitats as well as hard substrata, thus they have the potential to spread across the seabed among marine farms or into significant natural habitats. This means that even for sessile species with a restricted planktonic propagule duration (e.g. the sea squirt *Styela clava*), constraints on planktonic dispersal are not necessarily a barrier to local and regional spread (Forrest et al. 2009).

Considering the connectivity of farm blocks illustrated in Figure 2 (in Section 1.1.1), and on the basis of the above discussion, the characteristics of species for which the IMU concept would be most relevant are those with highly limited propagule dispersal (≤ 2 days) that also have a limited ability to inhabit soft sediments. The only species from Table 5 with these constraints are the Asian kelp *Undaria pinnatifida* and sea squirt *Didemnum vexillum*. Although the sea squirt *Styela clava* also has a limited larval duration (c. 1 day), evidence from the Firth of Thames (Grange et al. 2011) suggests that this species is likely to be able to establish in the soft sediments in the vicinity of the farm sites. As such, its establishment on any one of the farm blocks may eventually lead to its establishment on the others, irrespective of their low particle connectivity. Of course, it may takes years to decades for widespread establishment to occur by processes like seabed spread, such that management of anthropogenic pathways among farm blocks may still be worthwhile for sites of low connectivity. These types of management decisions need to be considered case-by-case, based on a systematic assessment of the nature and magnitude of the risk (considering also non-aquaculture risks), and the benefits and costs of risk management (e.g. Forrest & Sinner 2016).

6. HARMFUL ALGAL BLOOMS REVIEW

A number of microscopic planktonic algae (phytoplankton) produce toxins that can accumulate in filter feeding bivalves (e.g. GLM) and cause a variety of illnesses in shellfish consumers. These include: diarrhetic shellfish poisoning (DSP), amnesic shellfish poisoning (ASP), neuro-toxic shellfish poisoning (NSP), paralytic shellfish poisoning (PSP), spirolide and azaspiracid poisoning and some other less common types. Shellfish poisoning episodes occur as a result of sporadic, often seasonal, blooms of the causative phytoplankton species. These generally do not last longer than a few weeks but they leave a legacy of toxin residues in bivalves that may take weeks (green-lipped mussels) or months (tuatua) to be eliminated after the bloom is over.

The risk to shellfish aquaculture in the Bay of Plenty from most types of shellfish poisoning toxins is believed to be fairly low relative to other parts of New Zealand. The principal exception is PSP-toxin contamination, which historical data show is common and occasionally reaches dangerous levels. There have been a number of recorded cases (~30) of human paralytic shellfish poisoning in recent years due to the consumption of surf clams (tuatua) from the bay (ESR 2012; Murray 2013). Offshore shellfish aquaculture will undoubtedly be affected at times.

PSP is a potentially fatal condition and there are strict internationally prescribed levels of toxin residues (0.8 mg saxitoxin[5] equivalents/kg shellfish flesh) permitted in shellfish for local sale or export. Aside from the human health concerns, the inadvertent export of shellfish containing concentrations of PSP-toxin over the regulatory level would be very damaging to Bay of Plenty aquaculture and the New Zealand shellfish industry as a whole.

Before reviewing harmful algal blooms (HABs) in the BOP, we first provide some background on the approaches to monitoring HABs in the following section. Such approaches are currently used by the shellfish industry to protect the safety of consumers.

6.1. Monitoring approaches

There are two main approaches to monitoring:

1. Shellfish flesh sampling and analysis to detect and quantify biotoxins produced by phytoplankton.
2. Seawater sampling and analysis by microscopy for the presence and abundance of harmful phytoplankton cells.

[5] Saxitoxin is also referred to as STX.

Each of these approaches have advantages and disadvantages which we discuss below.

6.1.1. Biotoxin monitoring

Biotoxin monitoring focuses on the identification and quantification of toxic compounds in shellfish. Because shellfish filter large volumes of water, they can rapidly accumulate undesirable levels of toxin; however modern analytical methods are very sensitive and can detect a wide range of toxins at concentrations well below the regulatory prohibition levels.

In the last few years, important changes have been made to the methods used to test for PSP-toxins in shellfish. From 1993 to 2010 all testing was carried out using the standard mouse bioassay (MBA) method (APHA 1970; AOAC Official method 959.08). In 2010, because of technical (false positive and false negative results, poor sensitivity) and ethical problems associated with the MBA (including EU legislation limiting the use of animals for regulatory food testing) an assessment of alternative analytical methods was made. A chemical analysis method (Lawrence HPLC/pre-column oxidation method) was chosen and authorised for routine use by MPI in mid-2010, after a thorough evaluation of its performance (Holland et al. 2010).

Between 2010 and November 2013 a screening method (based on an abbreviation of the Lawrence HPLC method), designed to alert public health authorities to the presence or (absence) of toxins, was used by AsureQuality to screen Bay of Plenty shellfish samples. This method was adequate to identify bloom episodes but quantification was highly inaccurate and the toxicity values obtained during this period are unreliable. In November 2013 Cawthron took over all the marine biotoxin testing in New Zealand using the comprehensive Lawrence HPLC-FD method and reliable toxin quantification in Bay of Plenty samples is available from then on. In December 2015, a further important innovation was implemented through the development of a mass spectrographic method (LC-MS/MS) for the analysis of PSP-toxins (Boundy et al. 2015). This method is currently undergoing international validation trials but is already used for the analysis of all shellfish samples throughout New Zealand. The method is sensitive, highly specific for a large range of toxin analogues, and delivers accurate quantitation of total toxicity. It provides a high level analytical integrity and certainty for the protection of public health and the shellfish industry.

Limitations of sole reliance on biotoxin monitoring are that it may be difficult to predict future changes in the concentrations without knowing what is driving these changes. Also substantial investment is required in terms of the time needed for sampling, sample shipment, processing and analysis.

6.1.2. Phytoplankton monitoring

An important benefit of phytoplankton monitoring is that it can provide an early warning of the presence of harmful species before they reach numbers high enough to cause significant levels of biotoxins in shellfish to develop. Phytoplankton monitoring simply involves the collection of sea water samples for microscopic identification and enumeration of potentially harmful species. It has proven effective as an early warning of impending toxic blooms in areas such as the Marlborough Sounds. Algal blooms in this type of enclosed environment are often localised and routine sampling locations have been chosen to provide a good representation of the various water bodies within the region. Additional secondary sampling sites that provide better spatial resolution may be employed during bloom events. In extensive marine farm developments in exposed offshore regions such as the Bay of Plenty, movement of water parcels/masses may be large and unpredictable. Blooms may originate some distance from farmed areas, but move within short timeframes into marine farming zones. Therefore, it may be challenging to obtain water samples that are representative of the large water masses that could affect farmed shellfish.

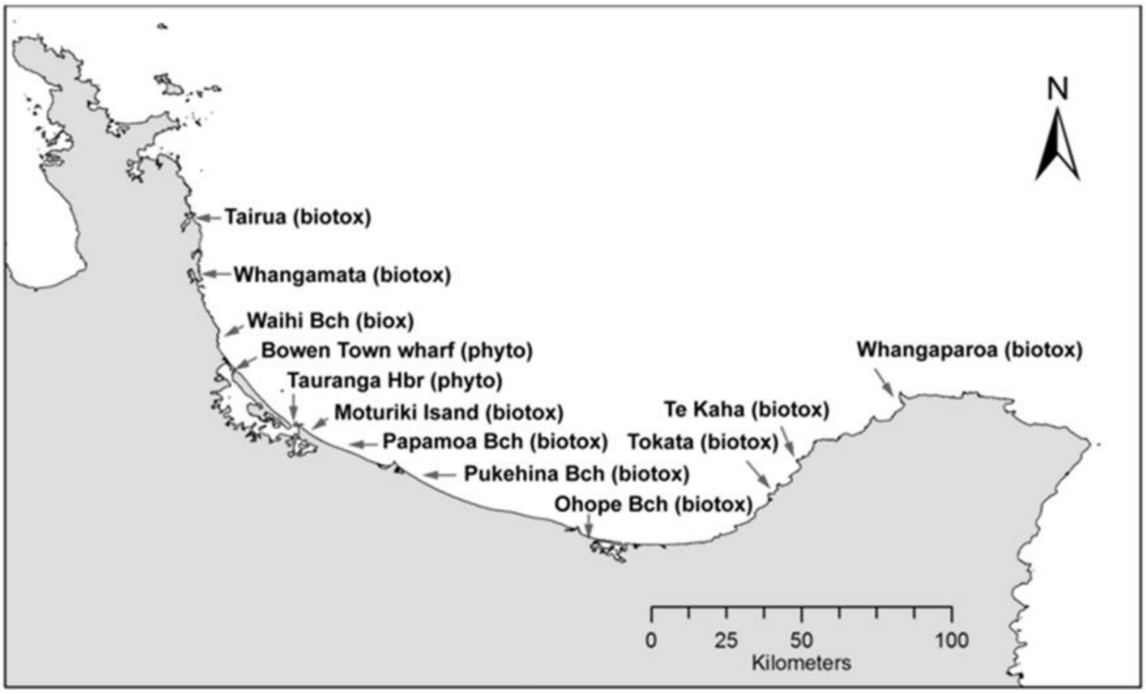

Figure 17. Shellfish biotoxin (biotox) and toxic phytoplankton (phyto) sites routinely or occasionally sampled under the public health protection monitoring programme by the Ministry for Primary Industries (MPI) in the Bay of Plenty.

Since the early 1990s a routine toxic phytoplankton and shellfish toxin monitoring programme has been carried out at a number of locations throughout the Bay of Plenty (Figure 17). The monitoring programme (coordinated and funded by MPI) is focussed on the protection of public health and involves weekly or fortnightly sampling of shellfish and sea water from 3-4 shoreline sites throughout the bay. The large amount of data that has been collected since the early 1990s has provided a good understanding of the incidence and severity of PSP-toxin contamination of shellfish on the sea shore. However, because of the nature of much of the coastline (surf beaches), it has been difficult to routinely obtain representative samples of offshore water (i.e. beyond the surf zone). Consequently, little is known about how cultured filter feeders suspended in the water column, 10 or more kilometres offshore will be affected. It is only recently, due to the establishment of the Opotiki mussel farm, that we now know that high numbers of *Alexandrium pacificum* and high levels of PSP-toxicity in cultured mussels occur offshore at the same time toxicity appears at other onshore sites in the eastern bay (Ohope, Te Kaha).

The current public health monitoring programme is not adequate to protect current and potential offshore aquaculture zones. Therefore it is important that routine toxic phytoplankton and shellfish biotoxin monitoring is extended to the offshore sites, to prevent contaminated products from entering the food chain. The establishment of offshore farms in the Bay of Plenty that will be regularly visited by vessels will enable higher-frequency sampling than has been feasible in the past.

6.2. *Alexandrium* spp. blooms and PSP-toxins in Bay of Plenty shellfish

Historical records from public health monitoring programmes (NZ Food Safety Authority, MPI) show that the Bay of Plenty has the highest incidence of significant marine biotoxin events in New Zealand. Periodic widespread PSP-toxin contamination of shellfish in the Bay of Plenty and elsewhere on the north-east coast of the North Island are due to the frequency of blooms of the planktonic dinoflagellates (Figures 17 and 18) *Alexandrium minutum* and *Alexandrium pacificum* (the latter previously known as *Alexandrium catenella*) (Chang et al. 1996, 1997; MacKenzie et al. 2004; MacKenzie 2014). Blooms of *A. minutum* may be the most hazardous because of the predominance of neo-saxitoxin (neoSTX), the most potent of the saxitoxin analogues (Munday et al. 2013) in this species.

Surf clams (*Paphies* spp. or tuatua) are abundant along the sandy surf beaches of the Bay of Plenty. The long term retention of toxin in surf clams such as tuatua means the Bay of Plenty sampling sites have always figured disproportionately in the national biotoxin statistics. In common with surf clams in other counties, PSP-toxins become tightly bound to the tissues within the syphons of tuatua which results in low but detectable levels existing for periods up to a year after the bloom that caused the original contamination (MacKenzie et al. 1996). The long term retention of PSP-toxins in tuatua is the reason why long recreational harvesting closures are common in the Bay of Plenty.

Not much is known about the environmental drivers, seasonality and dynamics of *Alexandrium* blooms in the Bay of Plenty. It is not understood why there appears to be alternating periods of abundance of *A. minutum* and *A. pacificum*, or why the former seems more common in the western side of the bay and the latter on the eastern side. The only existing data on the spatial distribution of cells in the bay during a bloom were provided by Chang et al. (1996). They first identified *A. minutum* in the western bay in January 1993 during a high cell density (> 1.2 x10^5 cells/litre) bloom that occurred when surface seawater temperatures were lower, and salinities higher than normal for this time of year. Cell numbers of *A. minutum* were highest close to the shore and generally decreased eastwards from Tauranga/Mt Maunganui. Chang et al. believed the bloom was associated with the near-shore upwelling of nutrient-rich waters in the western bay, possibly associated with the El Nino southern oscillation phase persisting at the time. The pattern of numerous subsequent *Alexandrium* spp. blooms however does not support the hypothesis that El Nino/La Nina climate anomalies play an important role in the occurrence of blooms.

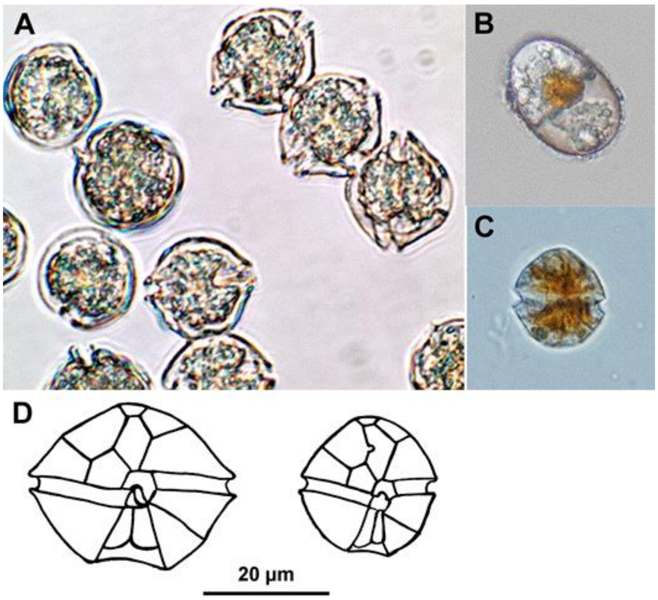

Figure 18. Morphology of *Alexandrium pacificum* (syn. *catenella*) and *Alexandrium minutum*. A. Motile cells of *A. pacificum* in a natural bloom sample. B. Benthic resting cyst of *A. pacificum*. C. Cultured cell of *A. minutum*. D. Relative sizes and thecal plate structure of *A. pacificum* (left) and *A. minutum* (right).

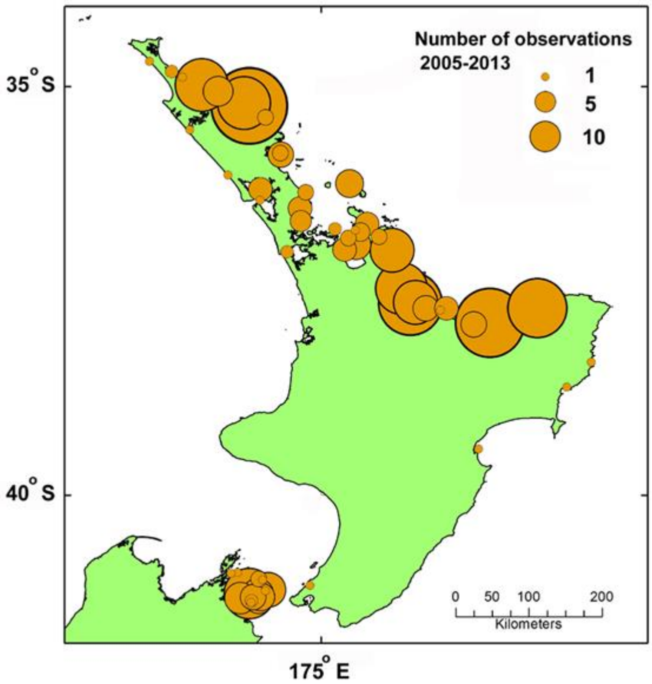

Figure 19. The number of observations of *Alexandrium pacificum* (syn. *catenella*) recorded at weekly phytoplankton monitoring stations, 2005–2013.

The first major PSP-toxin contamination event attributable to *A. pacificum* occurred in the eastern Bay of Plenty (Whangaparaoa, Ohope Beach) in late March 1996 (Figure 19 to Figure 21). The toxicity (determined by mouse bioassay) in green-lipped mussels (*P. canaliculus*) at Whangaparaoa reached a level of around 9 mg STX equiv'/kg (i.e. about 10 times the regulatory limit). The appearance of toxicity in shellfish progressed from east to west across the bay, and in late May, tuatua at western sites (Papamoa Beach) showed an increase in toxicity over background levels. The toxicity in the Whangaparaoa mussels declined rapidly and by early May no trace of PSP-toxicity could be detected. The toxicity of the Ohope Beach tuatua declined characteristically slowly and was still above the quarantine level in late September.

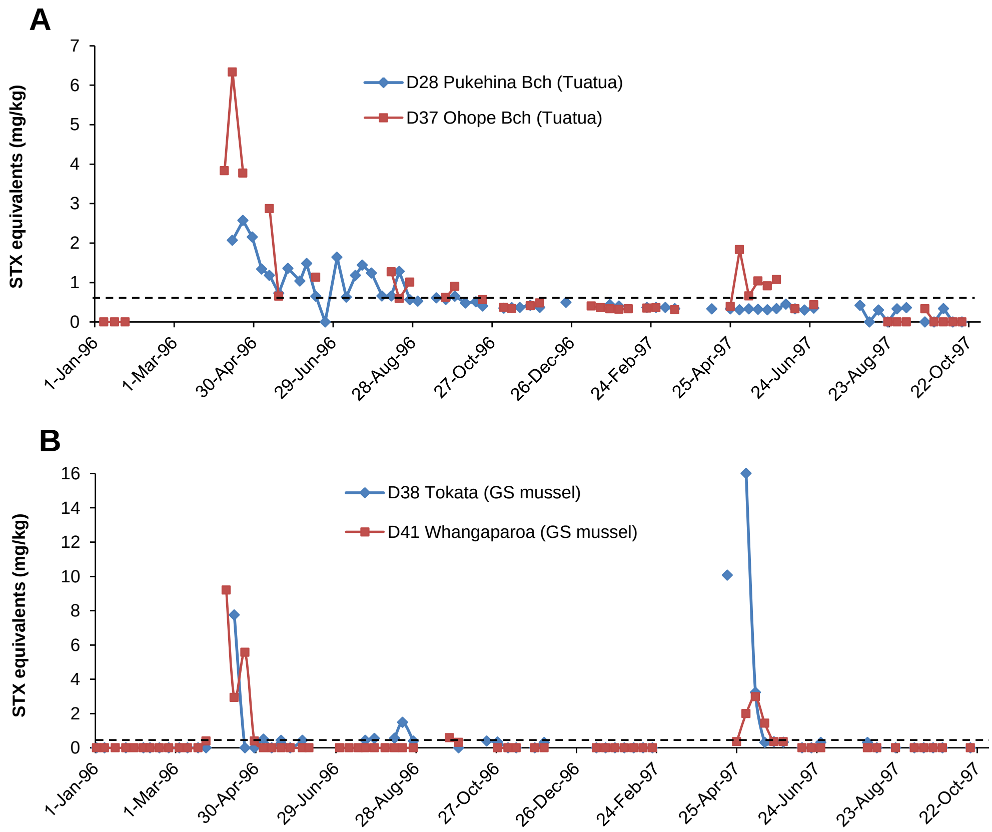

Figure 20. PSP-toxin accumulation and elimination in Tuatua from Pukehina and Ohope beaches and green-lipped mussels from Tokata and Whangaparoa (Cape Runaway) caused by blooms of *Alexandrium pacificum* in 1996 and 1997. Toxicity was determined by the mouse bioassay. On both graphs the dotted line indicates the regulatory level of 0.8 mg STX equivalents/kg.

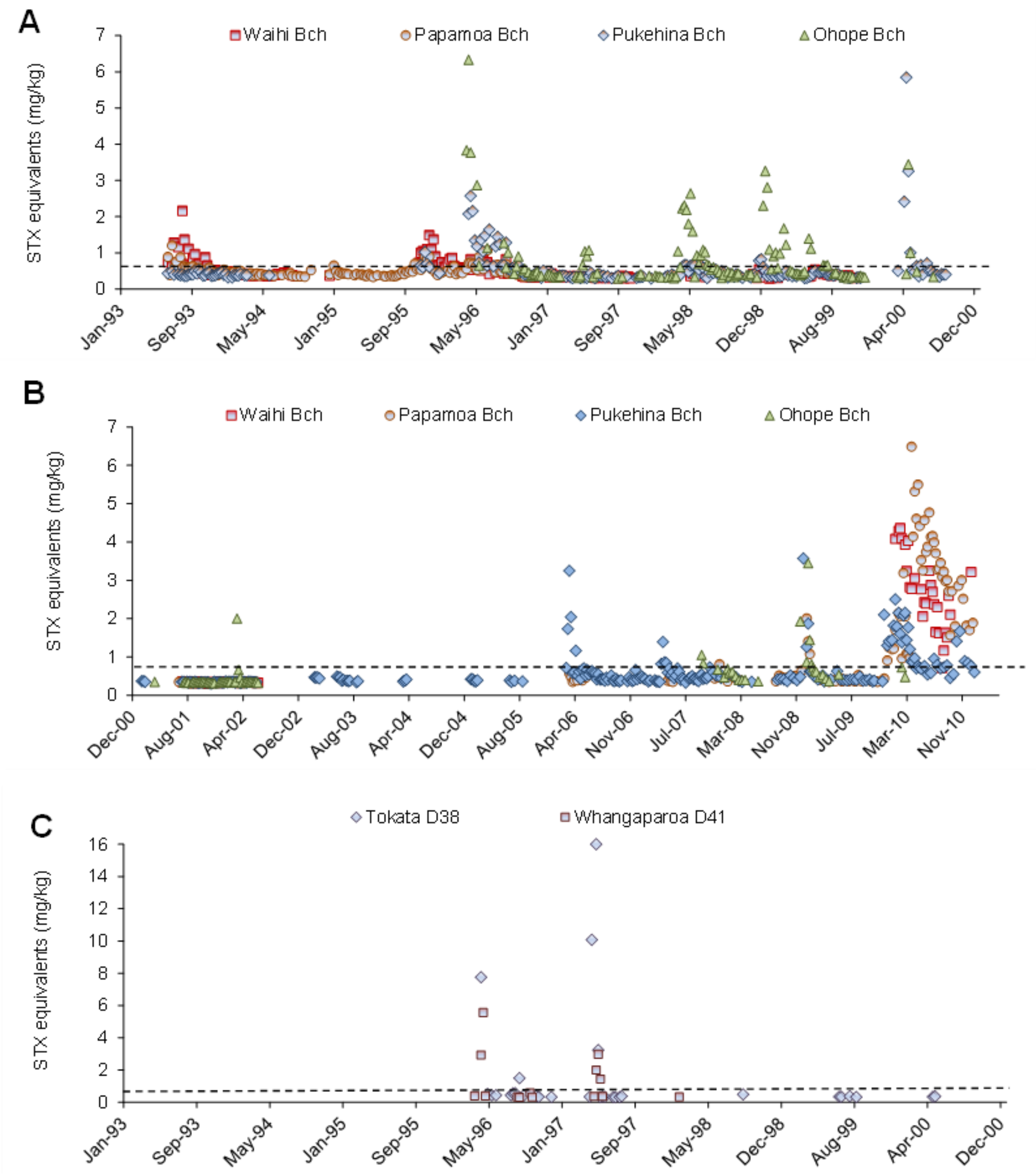

Figure 21. PSP toxicity scores at monitoring sites in the west-mid (A & B) regions of the Bay of Plenty (1993-2010) and in the east region of the bay (1993-2000) (C), associated with blooms of *Alexandrium* spp. Toxicity was determined by the mouse bioassay. On all graphs the dotted line indicates the regulatory level of 0.8 mg STX equivalents/kg.

An *A. pacificum* bloom re-occurred the following year (Figure 22C) and high levels of toxin (> 10 mg STX equiv'/kg) occurred in mussels in the eastern Bay of Plenty (Whangaparaoa, Tokata) in April 1997. Contamination progressed westwards across the bay as far as Ohope and Pukehina beaches but shellfish on beaches further to the north-west (Waihi and Papamoa) remained at normal low background levels. Maximum numbers of *A. pacificum* (1.1 x10^5 cells/litre) were observed at Te Kaha on

29 April 1997 associated with reports of cloudy, discoloured (brown) water in the area at the time.

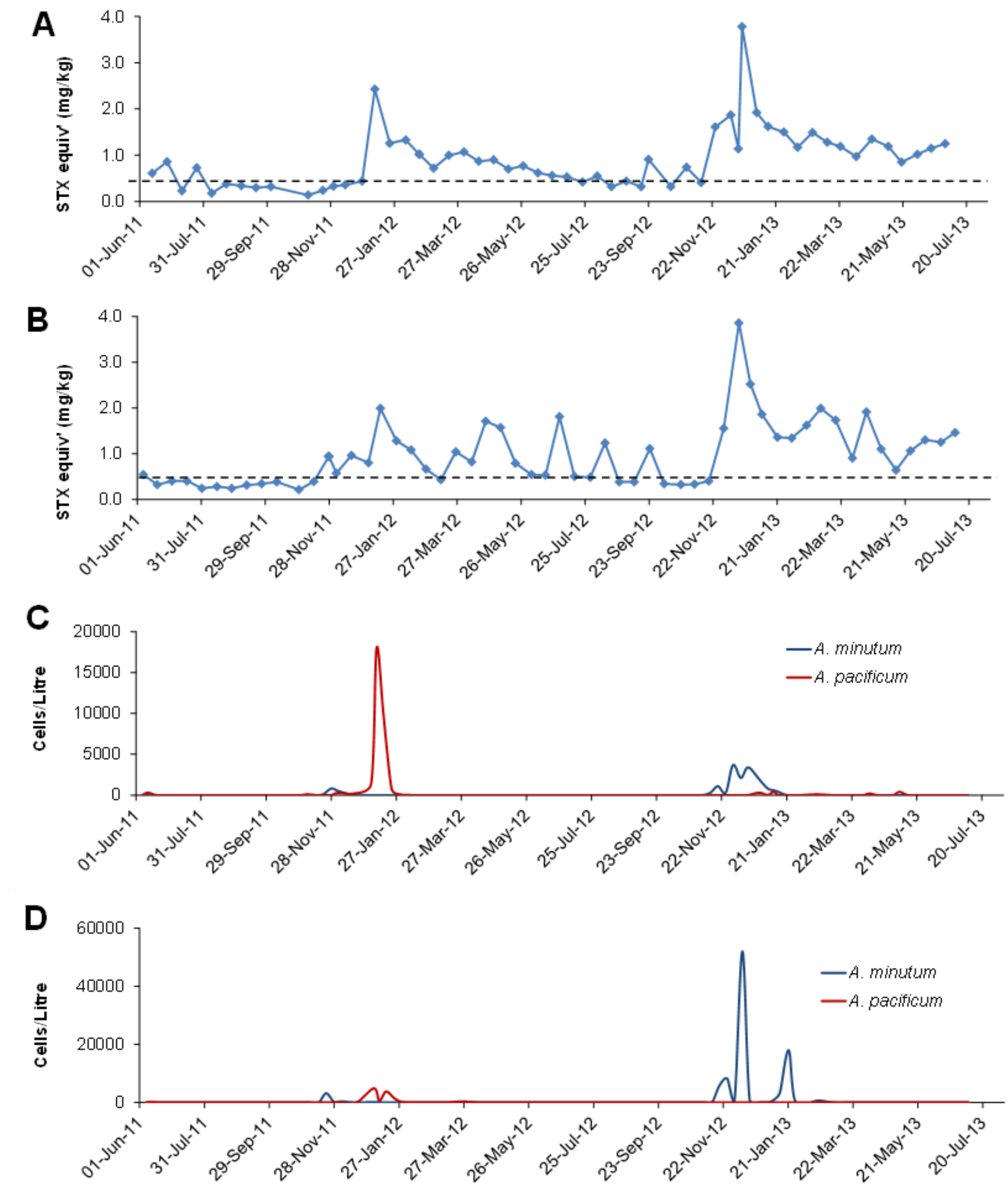

Figure 22. PSP-toxin levels (A & B: Assure Quality HPLC screen) in tuatua (*Paphies subtriangulata*) from Bay of Plenty beaches and cell abundance (C & D) of *A. pacificum* and *A. minutum* at Bay of Plenty phytoplankton monitoring sites, June 2011–June 2013. Tuatua sampling sites: Pukehina Beach (A) and Papamoa Beach (B). Phytoplankton monitoring sites: Tauranga Harbour (C) and Bowentown Wharf (D). NB. Precise quantification of shellfish toxicity from these data is not possible. The dotted line indicates the regulatory level of 0.8 mg STX equivalents/kg.

Bay of Plenty shellfish toxicity data (Figures 20 to 23) show that significant PSP contamination events are almost an annual occurrence in some parts of the BOP. In some years this is due to blooms of *A. pacificum*, and in others to *A. minutum*. Blooms can occur throughout the year, with mid-winter being the only time when events are rare. The Ohope Beach monitoring station has a long record of PSP-positive samples and is almost directly inshore of the Opotiki ESL mussel farm.

6.3. The consequences of undetected PSP-toxin contamination: the Tasmanian experience

In October 2012 the Australian shellfish industry suffered a serious setback, when Japanese health authorities found unacceptable levels of PSP-toxins in a shipment of blue mussels (*Mytilus galloprovincialis*), originating from the east coast of Tasmania (Campbell et al. 2013). This resulted in a global recall of products and extended closures (up to 100 days) of important bivalve production areas.

The shellfish poisoning was the consequence of a widespread but undetected bloom of the toxic dinoflagellate *Alexandrium tamarense*, a species which had been known to occur in this region for some time. The event caused an estimated direct revenue loss to the mussel industry of around $A 6.3 million, and around $A 0.8 million each to the scallop and rock lobster fisheries. When an economic multiplier was applied to this loss of revenue, the total economic impact was estimated at approximately $A 25.6 million. These losses were attributed to a breakdown in the Tasmanian Biotoxin Management Plan procedures which resulted in inadequate phytoplankton and shellfish toxin monitoring in the affected region, before and during shellfish harvest.

The Tasmanian event serves as a reminder to the New Zealand industry that complacency about the risks of PSP can have catastrophic effects. New Zealand's reputation as a supplier of high quality and safe seafood provides a competitive advantage and it is crucial that shellfish products containing unacceptable levels of PSP-toxin residues do not slip through the surveillance system and appear on local or international markets.

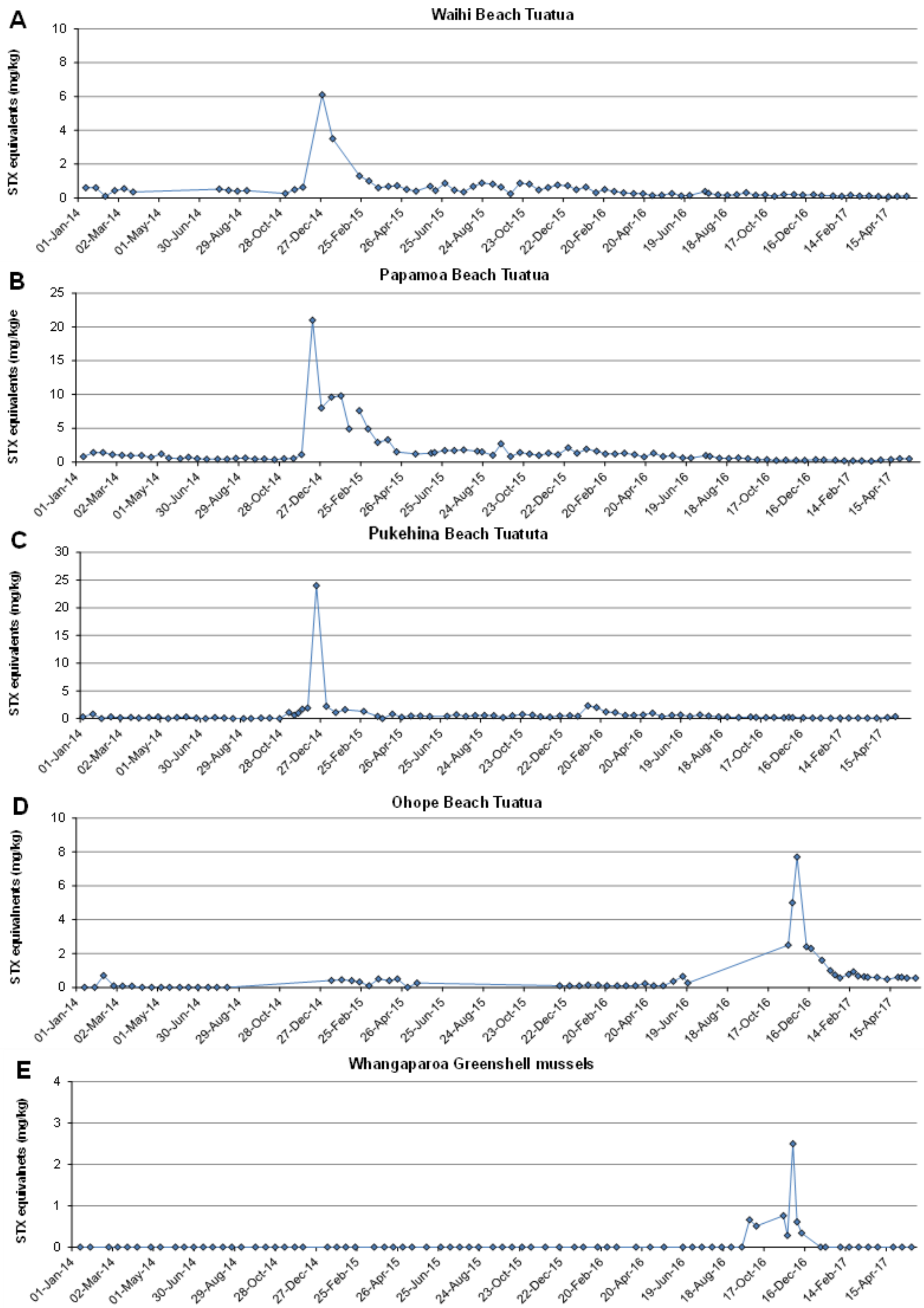

Figure 23. PSP-toxicity in tuatua (*Paphies* sp.) and green-lipped mussels (*Perna canaliculus*) analysed by LC-MS/MS from western (Waihi, Papamoa and Pukehina) mid-bay (Ohope) and eastern (Whangaparoa) monitoring stations, January 2014 to May 2017.

6.4. Summary

- There is a high risk that cultured shellfish in the Bay of Plenty will occasionally (possibly annually) be contaminated with paralytic shellfish poisoning (PSP) toxins due to blooms of the toxic dinoflagellates *Alexandrium pacificum* (syn. *catenella*) and *Alexandrium minutum*. Historical data show that shellfish contamination events are common in the BOP region, in some years due to blooms of *A. pacificum* in others to *A. minutum*.
- Current methods of shellfish biotoxin analysis (LC-MS/MS) are highly sensitive, specific, accurate and reliable. Phytoplankton monitoring provides a good method for the early detection of toxic blooms, but in the Bay of Plenty it has been constrained by the difficulty in routinely obtaining samples that are representative of offshore water masses. There is a large database that documents the frequency and intensity of historical near-shore contamination events.
- Most historical biotoxin data come from the routine sampling of surf clams (*Paphies* spp.). These are a good indicator of the onset of contamination events but, because of their slow rate of toxin elimination, they are not good indicators of bloom duration. Green-lipped mussels (*P. canaliculus*) rapidly assimilate PSP-toxins and also rapidly eliminate these after blooms have ceased.
- Until recently there was no information on how shellfish suspended in the offshore (~10 km) water column would be affected. However, due to the establishment of the Opotiki mussel farm, we now know that offshore cultured mussels can acquire toxins at the same time as onshore sites in the eastern bay (Ohope, Te Kaha).
- There are strict internationally prescribed levels of PSP-toxin residues permitted in shellfish and they are an important quality assurance issue for shellfish aquaculture in the Bay of Plenty. Consequently it is likely that there will be periods when shellfish will not be able to be harvested in this region. This is not unusual in some coastal shellfish aquaculture areas, and provided a suitable monitoring regime is in place, HAB events should be able to managed to ensure safe harvests are possible.
- The current public health monitoring programme is not adequate to protect offshore aquaculture zones and it is important that additional, routine toxic phytoplankton and shellfish biotoxin monitoring is extended to these regions. Biotoxin/toxic phytoplankton monitoring programmes have proven effective in preventing the harvest of contaminated products elsewhere in New Zealand; and a well-designed and rigorously implemented programme will no doubt be effective in the Bay of Plenty.
- Sea-cage finfish aquaculture is also susceptible to harmful effects from algal blooms. Although in the open ocean environment of the Bay of Plenty, the risk from most fish killing micro-algal species is probably much lower than in enclosed sheltered environments where these problems have been recorded in New

Zealand. It is however worth noting that finfish can also be affected by blooms of *Alexandrium* species (Mardones et al. 2015).

- There has been no systematic research on the ecology of *Alexandrium* species in the Bay of Plenty and not much is known about the dynamics, associated water column conditions and environmental and biological drivers of blooms. It will be important to carry out research to locate where in the bay blooms originate (i.e. the location of benthic cyst beds) and under what conditions resting cysts germinate. Coupled with hydrodynamic models, this knowledge will lead to a better understanding of how and over what time frames *Alexandrium* dispersion could impact aquaculture zones. Basic data on the hydrographic, water chemistry, climatic and biological conditions under which *Alexandrium* growth is enhanced and terminated will lead to better prediction.
- There is scope for the application of new genomics technologies and autonomous monitoring instruments to improve toxic phytoplankton surveillance. Cawthron Institute has recently secured funding for a small pilot project under the National Science Challenge, Sustainable Seas Innovation Fund to explore some of these options.

7. GAP ASSESSMENT FOR ECOLOGICAL EFFECTS

Any new aquaculture development will require a resource consent under the Resource Management Act 1991 (RMA). Because the actual farm locations and their size, or type have not yet been determined, specific assessment of the consent requirements are not covered here. Any applications resulting from this report are directed to the Bay of Plenty policy and planning framework, which prescribes the information requirements for resource consent applications in this region.

At a high level, MPI provides guidance regarding ecological effects of aquaculture (MPI 2013a), based on a review of available information (MPI 2013b). On the basis of this guidance, this section provides a high-level assessment of knowledge gaps regarding ecological effects of aquaculture development in the Bay of Plenty (BOP), with particular reference to the marine farm site locations discussed in previous sections.

In 2002, BOPRC began a broad-scale assessment of the suitability of the Bay of Plenty region for aquaculture (BOPRC 2002). The assessment included assessments of water column properties (Longdill et al. 2005b), water quality (Park 2005), currents and temperatures (Black et al. 2005), existing benthic (seabed) habitats (Longdill et al. 2005, 2007, 2008, Mead et al. 2005) and remote sensing of surface water properties (EBOP 2006). While useful at a broad scale (the majority of transects used in the studies were 10-20 km apart), finer-scale site-specific assessments will likely be required once final farm locations are identified.

Some site specific information has been collected for the existing ESL farm (e.g. Gibbs & Knight 2001; Hopkins & Robertson 2001), which may be relevant to new sites; however access to this information would need to be negotiated with ESL. Considerable information is now available on the existing levels of effects to the seabed (benthic) and water column from offshore mussel farms (MPI 2013a, 2013b). To date, no offshore finfish farms have been trialled in New Zealand, but recent developments in Storm Bay, Tasmania, may yield useful information in the near future. The large scale of the potential sites in the Bay of Plenty is such that a precautionary approach to development is suggested. A staged approach to development is one mechanism that has proven useful in other aquaculture areas (e.g. Tasman / Golden Bay aquaculture management areas), ensuring effects remain within those predicted as the area and / or intensity of farming is increased.

The specific ecological effects that are likely to require consideration for the proposed sites, and whether or not there are knowledge gaps relating to these effects, are summarised below (Table 6). The choice of main categories (benthic effects, marine mammal interactions, etc.) in the gaps analysis was based on those described by the MPI (2013a, 2013b) literature review and overview. The sub-categories reflect the primary mechanisms of effects that will require assessment and whether or not they apply to finfish farming or shellfish farming (or both), which were also derived from the MPI report and its underpinning studies. These sub-categories capture the primary effects that may arise from aquaculture, but do not necessarily reflect every conceivable effect that will require assessment.

Table 6. Knowledge gaps for proposed farm areas in the Bay of Plenty region. Ecological effects categories, potential assessment required, need for assessment depending on farming type (feed-added pens, suspension of filter-feeders and seaweeds, or both), and whether or not a knowledge gap exists.

Ecological effect	Potential assessment	Need for assessment by farming type (feed-added pens, suspension of filter-feeders and seaweeds, or both)	Knowledge Gap
Water column	Hydrodynamic and wave modelling	Both	Update model
	Phytoplankton depletion	Filter-feeding	Update model
	Nutrient enrichment	Feed-added	Yes
	Harmful Algal Blooms	Both	No
Seabed	Existing habitats (i.e. infauna /epifauna)	Both	Yes
	Organic enrichment/ habitat modification (shell drop)	Both	No
	Physical disturbance	Both	No
	Depositional modelling	Both	Yes
	Shading	Both	No
Marine mammal interactions	Entanglement risk	Both	Yes
	Habitat exclusion or modification	Both	Yes
	Effect on behaviour	Both	Yes
	Noise and lights	Both	Yes
Wild fish interactions	Habitat exclusion or modification	Both	Yes
	Effect on behaviour	Both	Yes
	Noise and lights	Both	Yes
Seabird interactions	Entanglement risk	Both	Yes
	Habitat exclusion or modification	Both	Yes
	Effect on behaviour	Both	Yes
	Noise and lights	Both	Yes
Biosecurity	Increased risk of introduction and spread of pests	Both	Partial
	Increased risk of introduction and spread of disease (pathogens and parasites)	Both	Yes
	Status of proposed species (i.e. indigenous or introduced)	Both	Yes
Escapee and genetics	Ecological effects of escapees	Both	Yes
	Changes to the genetic structure / fitness of wild populations	Both	Yes
	Effects of spat/ smolt transfer from other locations	Both	Yes
Additives	Effects relating to use and release of chemicals and therapeutants, including trace metals	Feed-added	Yes

8. CONCLUSIONS

Based on this preliminary assessment, it appears a combination of the modelled sites (up to c. 16,000 ha of new area) could potentially be managed for additional green-lipped mussel or other shellfish farming to avoid exceeding the carrying capacity and mitigating biosecurity risk. Nevertheless, in discussions with BOPRC, it is not clear what mix of aquaculture is likely to be undertaken in the region in future (i.e. shellfish, finfish or seaweed). The choice of species to be cultured should be considered with regard to the environmental characteristics of each site. This will ultimately determine the potential for use of the space in the areas considered here.

As with the existing consented site, new areas will face some challenges to development due to the relatively low currents in the region (mean of 4-6 cm/s). This implies that a low-intensity approach to farming for most forms of aquaculture is probably appropriate. However, this initial scoping study suggests that potentially large areas may be viable provided appropriate management of biosecurity and HAB risks are implemented and a cautious approach to development is undertaken. Consequently, even if low intensity farming is undertaken, substantial aquaculture production over the large areas considered here and within sustainable limits may be possible.

A substantial and growing amount of information exists on the effects of aquaculture in NZ (e.g. MPI 2013, 2013b); nevertheless, some knowledge gaps still exist in our understanding of its long-term effects. It is particularly relevant in the BOP region, in which limited aquaculture development has occurred to date. As a consequence, limited empirical data is available to support an assessment of the sensitivity of this environment to aquaculture development. Hence, if a large new area of development (e.g. > 1,000 ha) is considered, it would be prudent to consider a staged-approach that would allow for appropriate environmental assessments to occur as development proceeds.

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11. APPENDICES

Appendix 1. Additional details on the hydrodynamic model (provided by MetOcean Solutions, April 2017).

The POM (Princeton Ocean Model) is a primitive equation ocean model that numerically solves oceanic current motions (Mellor, 2004). POM has been used for numerous scientific applications studying oceanic and shelf circulation.

Model Equations

For the hindcast simulations, POM is used in a vertically integrated two-dimensional mode, solving the momentum and mass conservation equations given by:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho}\frac{\partial P_a}{\partial x}+A_H\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\tau_w^x}{\rho h}-\frac{\tau_b^x}{\rho h}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}-fv=-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho}\frac{\partial P_a}{\partial y}+A_H\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\tau_w^y}{\rho h}-\frac{\tau_b^y}{\rho h}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial(u[h+\eta])}{\partial x}+\frac{\partial(v[h+\eta])}{\partial y}=0 \qquad \text{(1.1a,b,c)}$$

where t is the time, u and v are the depth-averaged velocities in the x and y directions respectively, h the MSL depth, η is the elevation of the surface, g the gravitational acceleration, f the Coriolis parameter, ρ the density of water, and P_a is atmospheric pressure.

A_H is a horizontal eddy viscosity coefficient, calculated with a Smagorinsky parameterisation:

$$A_H=C_m\Delta x\Delta y\frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right]^{\frac{1}{2}} \qquad \text{(1.2)}$$

with C_m set at 0.2.

The surface and bottom shear stress, τ_w and τ_b are due to wind and bottom friction, respectively. The bed shear stress is parameterised with a quadratic type friction law:

$$\tau_b^x=C_D\sqrt{(u^2+v^2)}u \quad \tau_b^y=C_D\sqrt{(u^2+v^2)}v \qquad \text{(1.3a,b)}$$

that depends on an adjustable drag coefficient, C_D ~ 10-3

The wind shear stress is parameterised by:

$$\tau_w^x=\rho_a\gamma|W_{10}|W_{10}^x \quad \tau_w^y=\rho_a\gamma|W_{10}|W_{10}^y \qquad \text{(1.4a,b)}$$

where *ρa* is the density of air and *γ* is a coefficient given by:

$$\gamma = \left(A + B\left|W_{10}\right|\right)\times 10^{-3} \qquad (1.5)$$

in which W_{10} is the wind velocity at 10 m above mean sea level and A and B are adjustable coefficients with magnitude A~10-3 and B~10-4.

The model equations are solved with finite differences and explicit time-stepping, limited by a Courant condition.

Model domain and boundary conditions

For the hydrodynamical modelling of the Bay of Plenty (BOP), considering the domain size and the spatial resolution required for the area of interest, a nested approach was adopted. A parent grid with 0.06° spatial resolution (approximately 6 km) resolving barotropic tidally-induced and residual currents in a POM 2D implementation POM 2D algorithm modified by MetOcean Solutions Ltd) was run for the entire New Zealand area (POM NZ). This parent domain was forced at the open boundaries by 1/12 deg OTIS (OSU Tidal Inversion Software) Pacific Ocean tidal elevations and current amplitudes/phases (Egbert & Erofeeva 2002), while the POM BOP nest was forced by the total elevation and current from POM NZ. The POM BOP was run over 12 years (2000-2011) with 0.008 deg spatial resolution (approximately 800 m).

Atmospheric forcing of both POM NZ and POM BOP domains consisted of wind and mean sea level pressure fields obtained from a 37-year regional atmospheric hindcast carried out by MetOcean Solutions Ltd. The WRF (Weather Research and Forecasting) model was established over all New Zealand at hourly intervals and 12 km resolution. The hindcast was specifically tuned to provide highly accurate marine wind fields for metocean studies around New Zealand. The WRF model boundaries were sourced from the CFSR (Climate Forecast System Reanalysis) dataset distributed by NOAA (Saha et al. 2010). These data span 37 years (1979-2015) at hourly intervals and 0.31° spatial resolution.

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Appendix 2. Additional results and analysis from the particle tracking modelling.

Figure A2.1 to Figure A2.6 show results for particle releases from Farms 1-6. The white numbers below the farm number gives the fraction of particles from the source farm that arrived at the other farms within the given time frame. For example, only 0.09 or 9% of particles released from Farm 1 arrive at Farm 3 within 2 days, with 25% arriving within 10 days.

The colours indicates how often particles are seen within each of the 800m grid box of the hydrodynamic model after 1 day, 2 days, 5 days and 10 days. Thus the colours give a 'heat map' of how many particles are seen with each grid box over a two year period, where each particle exists for up to 14 days after it has been released. The arbitrary colour scale has been arranged so that the grid boxes with the most particles are in dark red. These dark red areas are concentrated around the farm where particles were being released. The colours of the heat map have been adjusted so that average number of particles for grid boxes which fall inside the releasing farm is set to be dark red for all examples shown. In addition, the colours are spaced on a log scale, as the number of particles falls rapidly with distance from the farm. Thus, the heat map colours exaggerate the extent of the area of covered by the particles, by over emphasising the small numbers of particles seen in the green and blue regions more distant from the releasing farm. Figure A2.7 shows how far particles have typically moved from their release point, thus gives a more realistic estimate of the size of the area covered by the particles in the heat map.

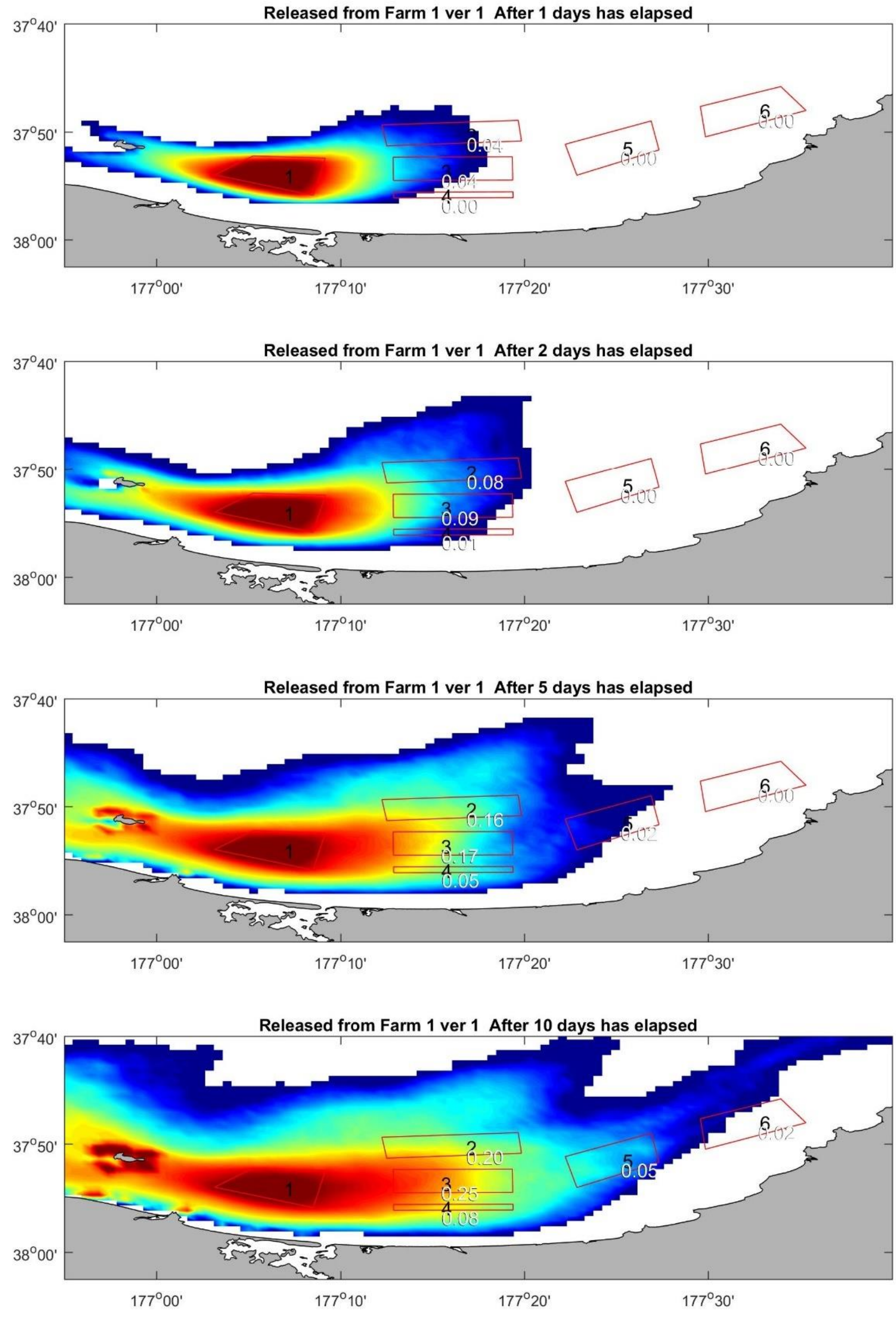

Figure A2.1 Heat map of observed particle locations after given time intervals after release from Farm 1. White numbers give fraction of released particles arriving at the other farms before the given time has elapsed.

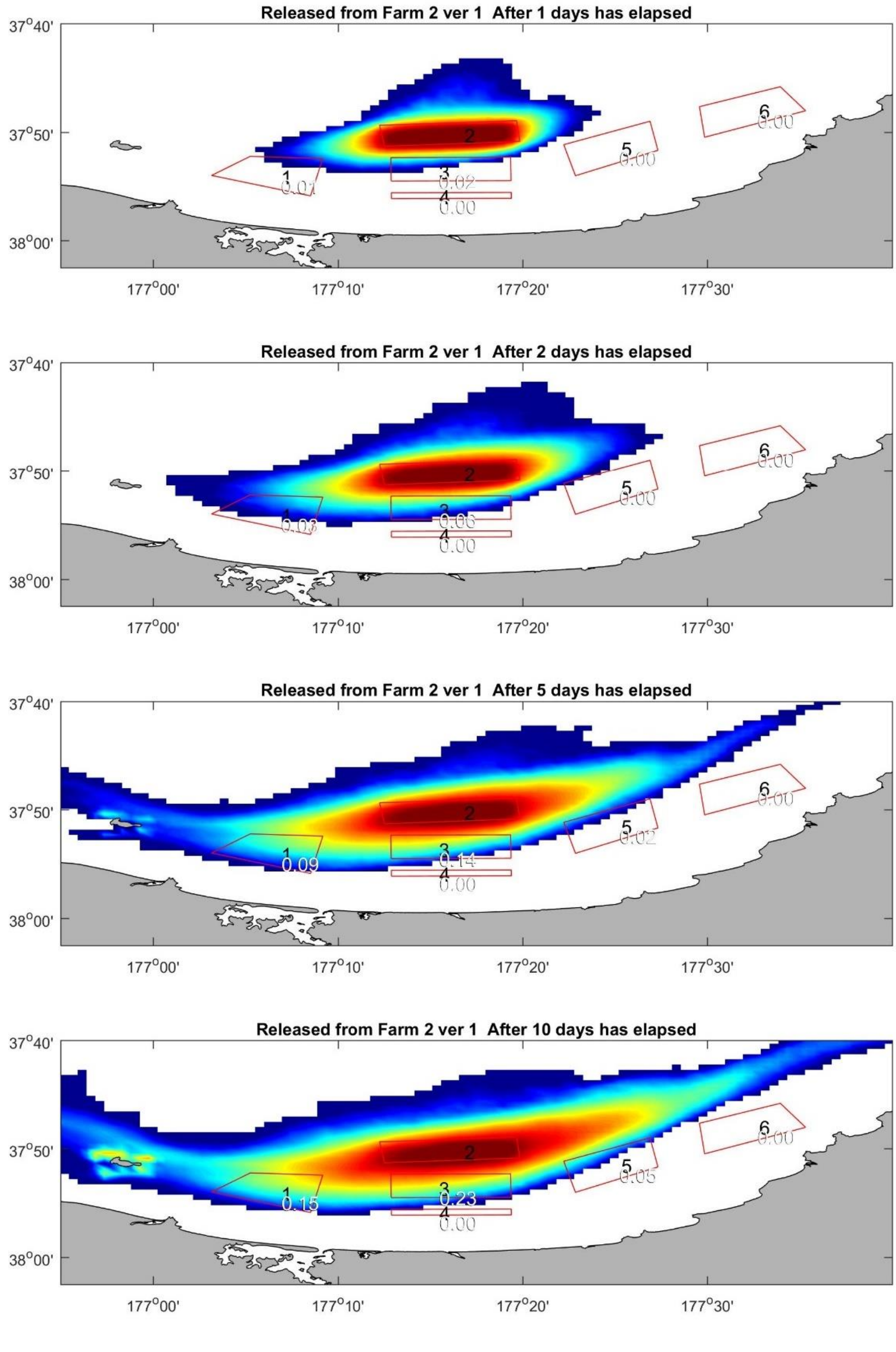

Figure A2.2. Heat map as in Figure A2.1 but for releases from Farm 2.

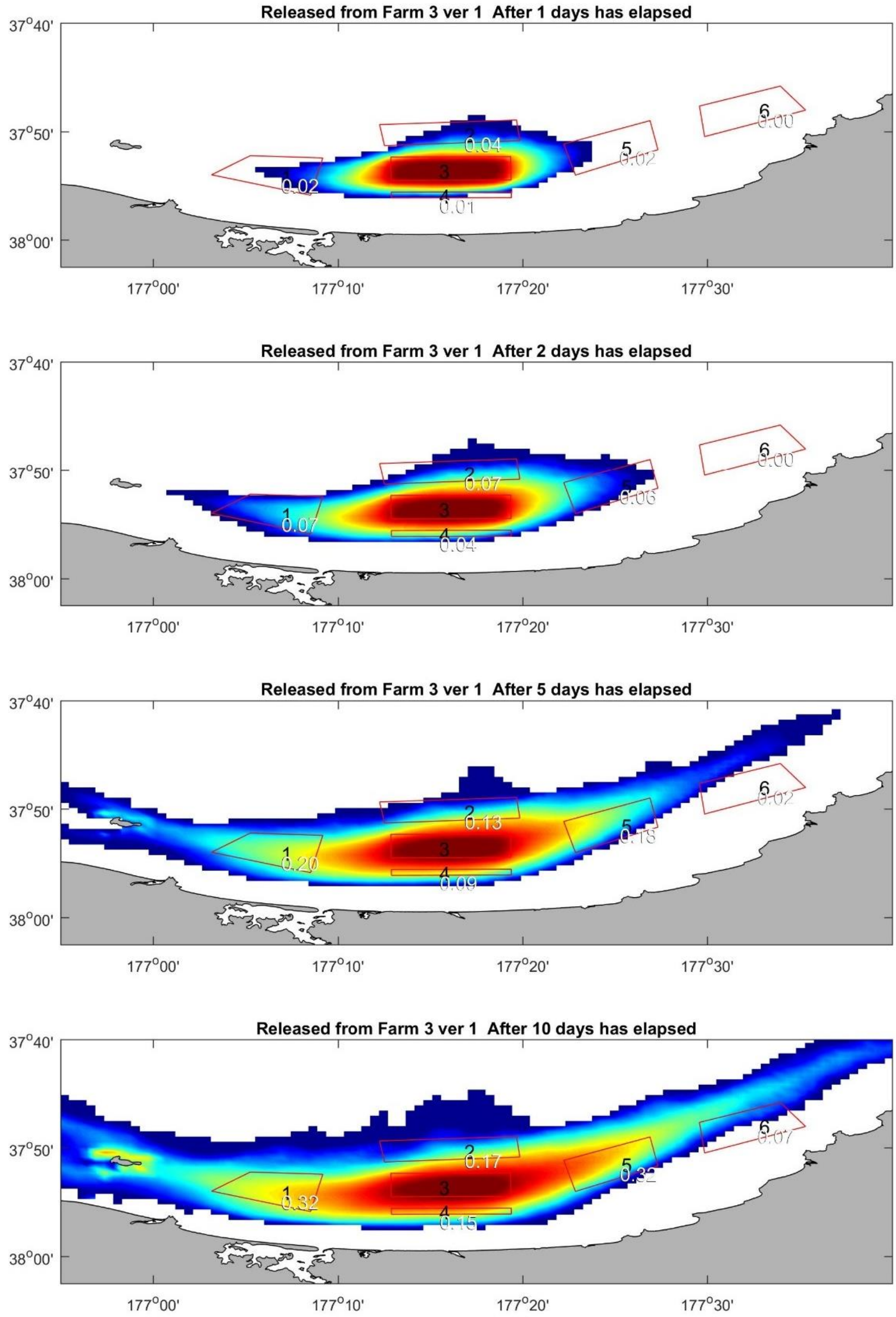

Figure A2.3. Heat map as in Figure A2.1 but for releases from Farm 3.

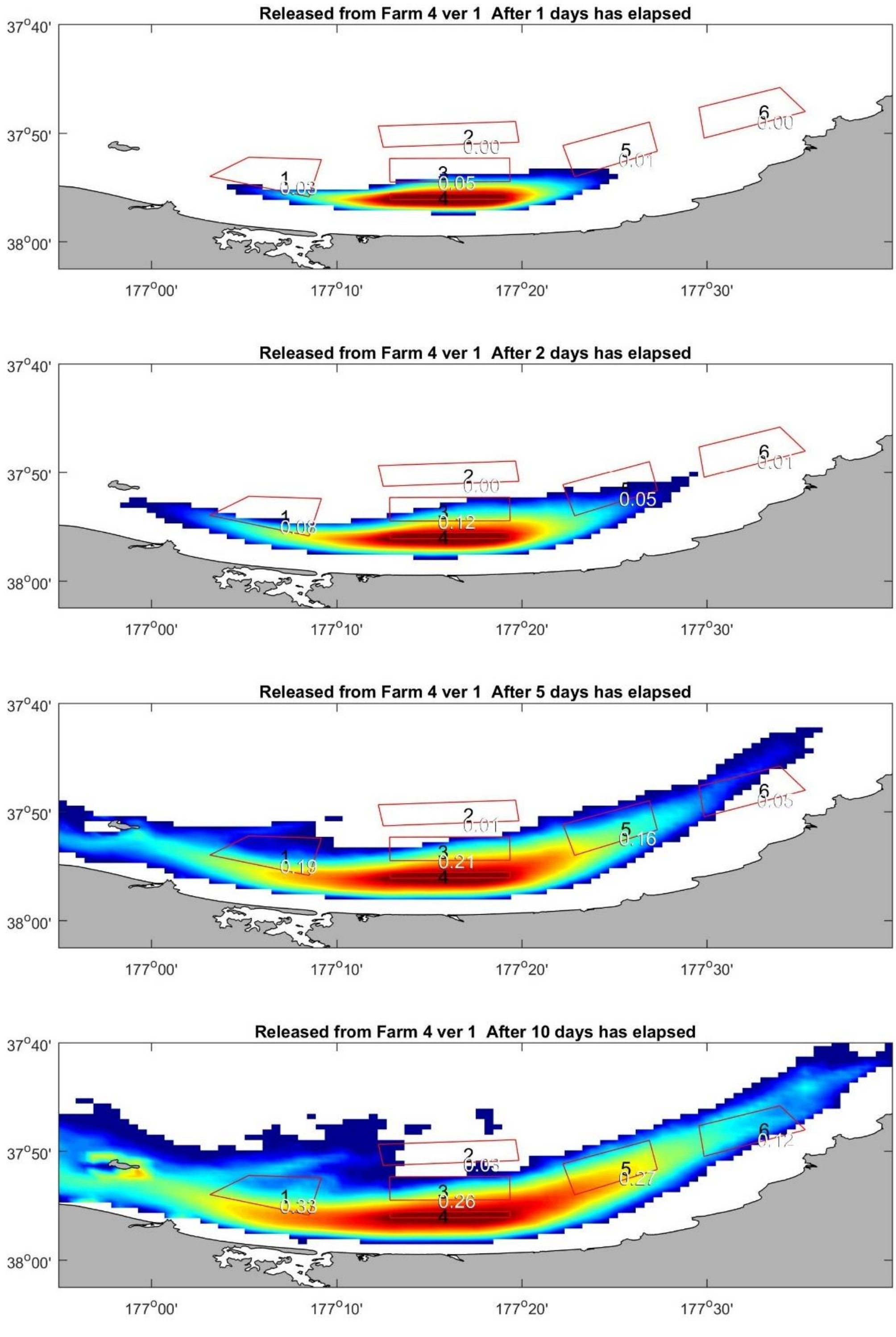

Figure A2.4. Heat map as in Figure A2.1 but for releases from Farm 4.

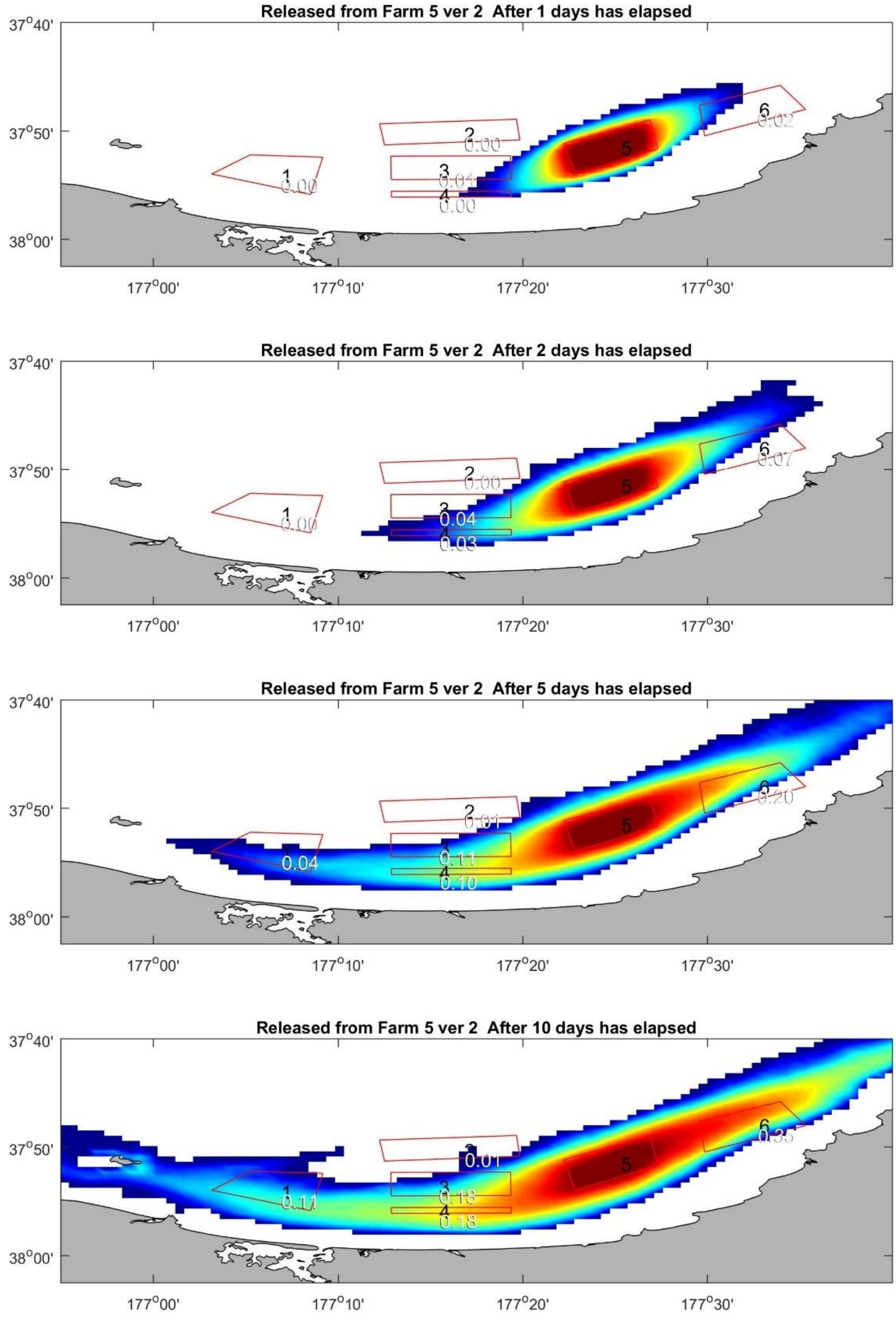

Figure A2.5. Heat map as in Figure A2.1 but for releases from Farm 5.

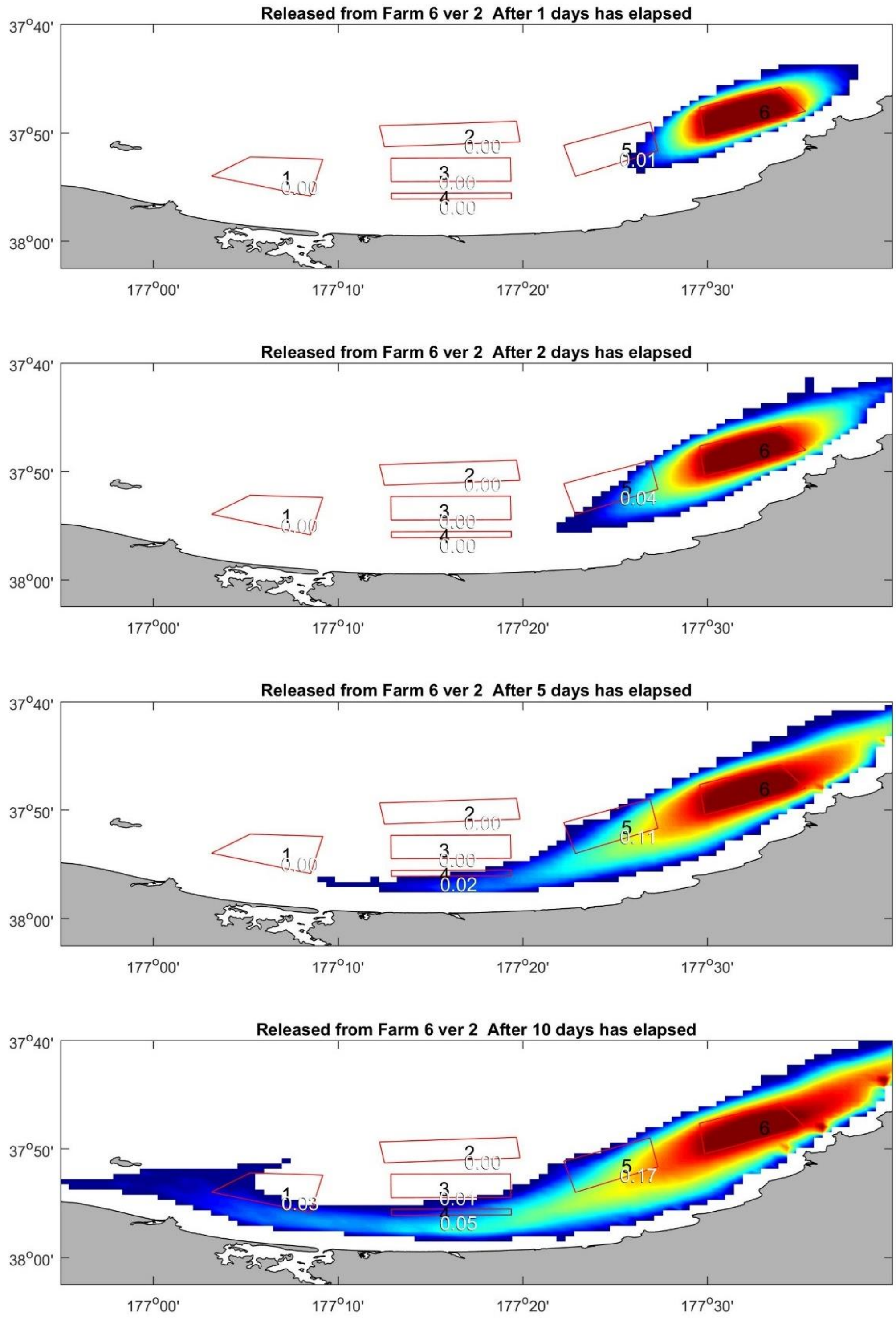

Figure A2.6. Heat map as in Figure A2.1 but for releases from Farm 6.

Displacement statistics

Figure A2.7 gives statistics of how far particles have travelled from their release point after a given number of days. The median particle displacements are typically 5 km after 2 days and 13 km after 14 days. These displacements are for all particles traveling in all directions, not just those that encounter another farm. They are useful in indicating how large the cloud of points is around the farm from which they are released in the preceding heat map figures. As context, farms 1 and 3 are separated by 5 km, while farms 3, 5 and 6 have 4 km between them.

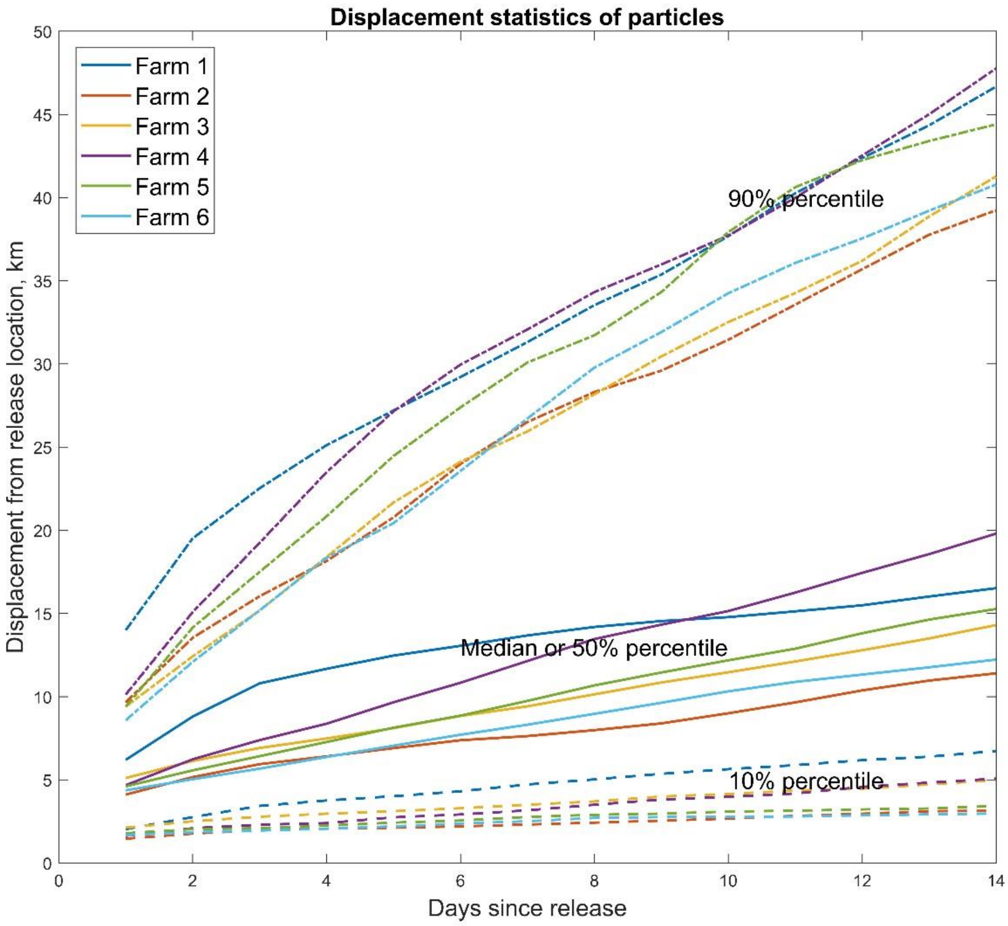

Figure A2.7. Displacements of particles from their release point at 1-14 days after release. Colour indicates which farm particles were released from. Middle solid curves give median displacement. 90% of particles were displaced by less than the values given by the upper chain dashed set curves. 10% of particles were displaced by less than the lower dashed set of curves.

Connectivity statistics

Figure A2.8 summarises the connectivity for the combinations of source farm and receiving farm, at 1-14 days after release, from forward particle tracking. These plots give the fraction of released particles, which pass through another farm, the same type of values given by the white numbers in the heat maps in Figure A2.1 to Figure A2.6, but for all 14 days after release. For example the upper left plot shows that 10 days after they are released from Farm 1 that 0.25 or 25% of particles have passed through Farm 3, while 20% have passed through Farm 2.

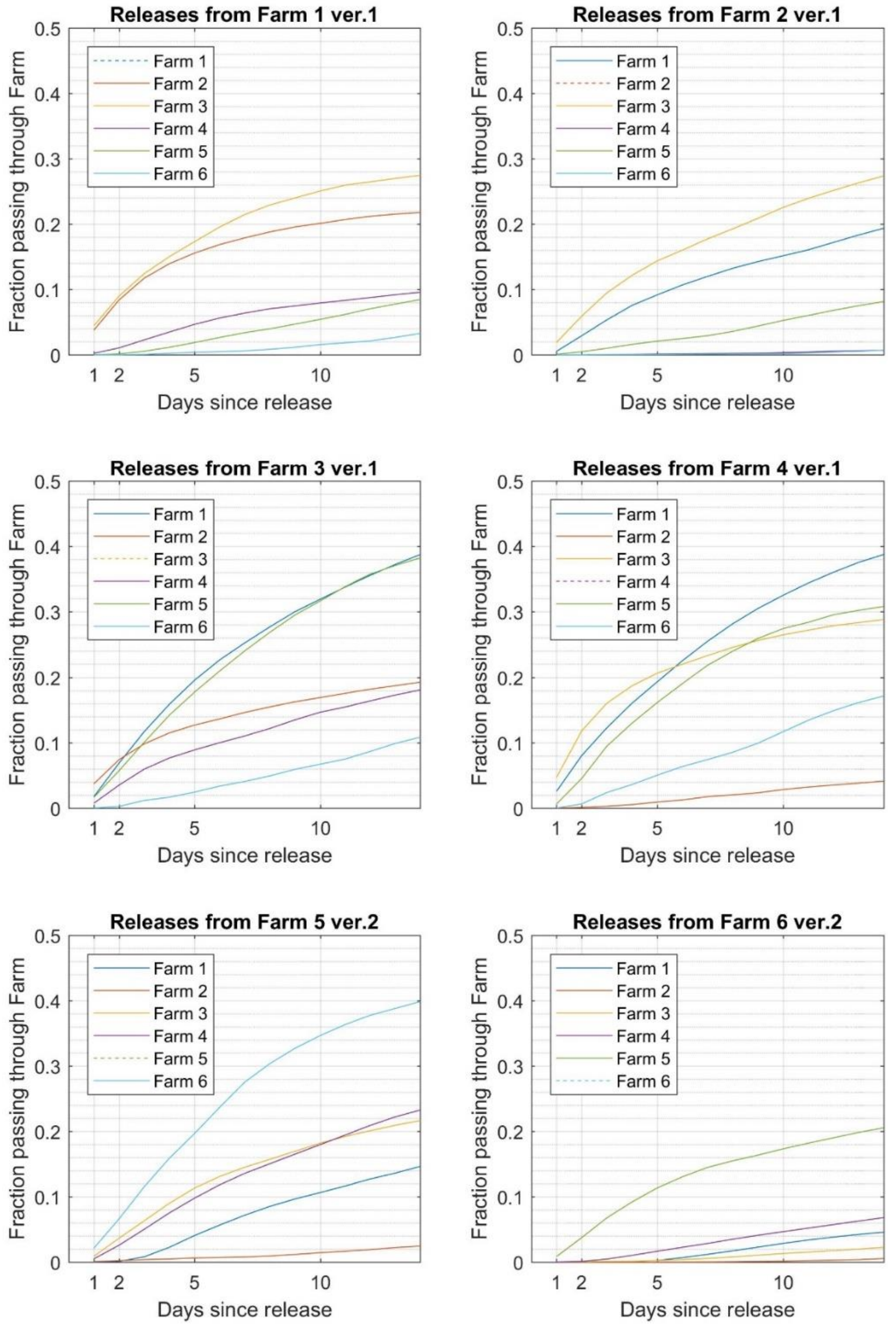

Figure A2.8. Curves show fraction of particles released from each farm arriving at other farms after given times in days. Legend shows colour of curve for farm where particles arrive. Summarises all the forward particle tracking results.

Figure A2.9 derived from the backward particle tracking is similar to Figure A2.8, but shows the fraction of particles arriving at a farm, which have passed through another farm. For example the yellow Farm 3 curve in the upper left plot, shows that of the particles which arrived at Farm 1, 25% had passed through Farm 3 at some time in the previous 10 days.

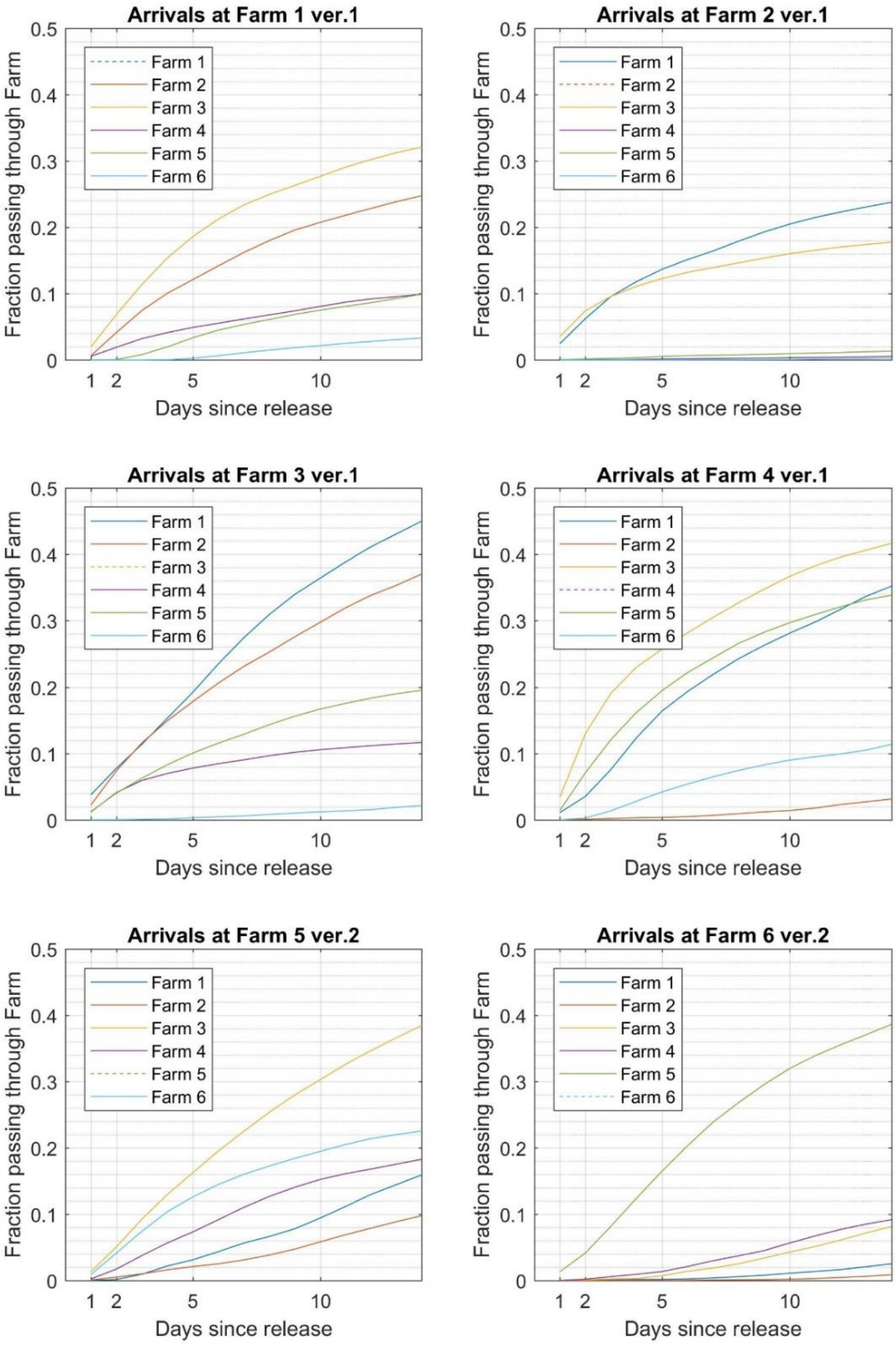

Figure A2.9. Curves show fraction of particles arriving at each farm which were released within other farms after given times in days. Legend shows colour of curve for farm releasing particle. Summarises the backward particle tracking results.

Test of sensitivity of results to particle release locations

Particles were released at random locations within each farm. To test the sensitively to this random choice, 20 sets of 70,000 particles were released randomly within Farm 3.

Curves are shown for these 20 sets of model runs (Figure A2.10). The curves are almost indistinguishable, demonstrating that a sufficiently large number of particles have been released, so that there is a very low sensitivity to the choice of where the particles are released within the farm. The fractions of particles arriving at the other sites varied by less than 0.01 amongst the 20 curves shown. This indicates the results given in Figure A2.8 and Figure A2.9 are not sensitive to where within the farm those particles were released.

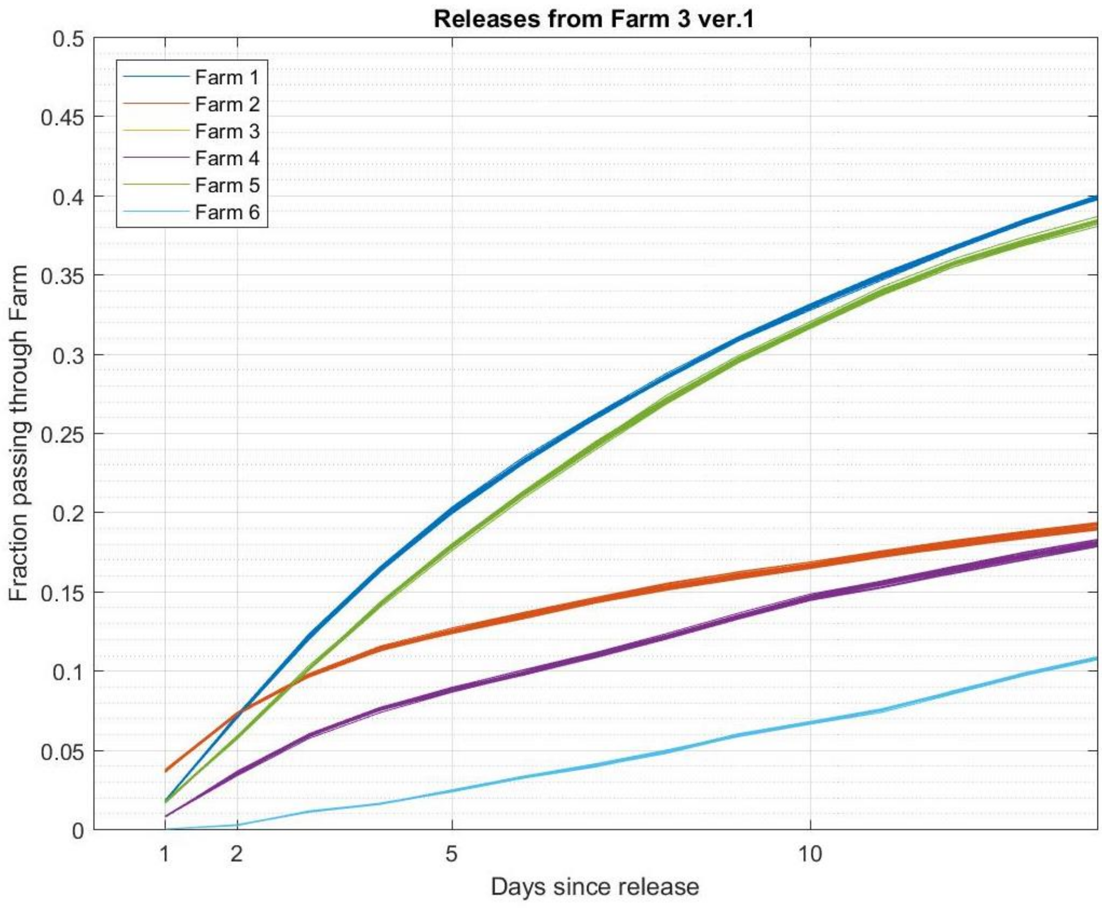

Figure A2.10. As for Figure A2.8, but showing curves from 20 repeated releases of 70,000 particles each from Farm 3 only.

Test of sensitivity of results to horizontal eddy diffusivity

ERcore particle tracking simulates the movement, or advection, of virtual particles using currents from a hydrodynamic model. This model has finite resolution of around 800m, and cannot resolve movement due to turbulent fluid motions on scales smaller than this. A standard approach, used within ERcore, is to incorporate the effect of sub-grid scale turbulence as a this random walk depends on the horizontal eddy diffusivity coefficient, K_H. There is an extensive history of research directed at estimating the size of K_H, with estimated values ranging over 2-3 orders of magnitude (James 2002; Souza et al. 2012). For this work a value of $K_H = 0.1\ m^2/s$ was used. The sensitivity of results to this value was tested by repeating particle tracking for 70,0000 releases from Farm 3 for $K_H = 0.01\ m^2/s$, $0.1\ m^2/s$ and $1.0\ m^2/s$. Figure A2.11 shows the fractions of particles arriving at the other farms for these three values of K_H. The curves are insensitive to the value used for K_H, with the fractions arriving at farms typically differing by less than 0.02.

The coastal ocean is typically dominated by advection processes, rather than horizontal mixing (Souza et al. 2012). A measure of the relative importance of these processes is the Peclet number, $P_e=UL/K_H$, where U is the velocity scale, L the horizontal length scale. Taking a typical model U=0.1 m/s and L=800m as the model grid scale, gives P_e = 8000, 800, 80 for $K_H = 0.01\ m^2/s$, $0.1\ m^2/s$ and $1.0\ m^2/s$ respectively. These high values of P_e confirm that advection processes would be expected to dominate diffusive mixing in the Bay of Plenty, thus the insensitivity of the connectivity statistics to K_H as shown in Figure A2.11 is not unexpected. This indicates that connectivity statistics are mainly driven by the physical movement of particles due to the currents resolved by the hydrodynamic model, rather than by sub grid scale turbulence causing particles to move through diffusion.

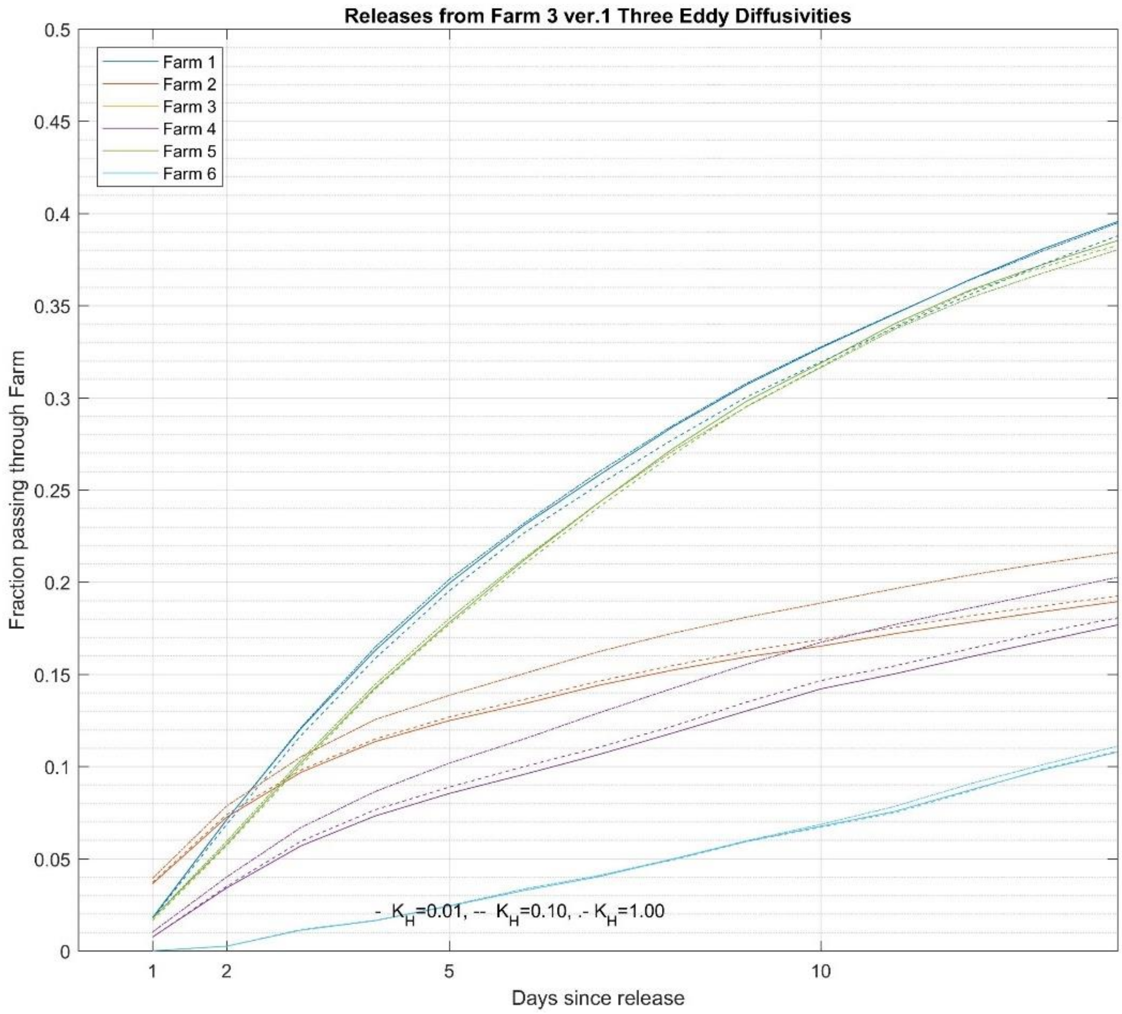

Figure A2.11. Test of sensitivity of connectivity statistics to horizontal eddy viscosity for K_H =0.01 m^2/s, 0.1 m^2/s and 1.0 m^2/s.

Durations particles spend within the farms

The connectivity between the farms is not only affected by the probability of a particle traveling from one farm to another, but also how long a particle spends within the second farm. Figure A2.12 shows how long on average particles released from one farm spend with another farm, after a given number of days since their release. Typically, the longest times are spent within the farm where particles were released. There are exceptions; e.g. particles released from the smaller Farm 4 often spent more time in the other farms, which all have a much larger area.

Figure A2.12 shows that particles which then pass through another farm, typically spend less than 2.5 days on average within the second farm. Particles which arrive at another farm within 2 days of release, typically spend less than 0.5 days within that farm. The average time spent within the second farm is around 1-1.5 days within 14 days of release.

The times in Figure A2.11 represent the total time on average particles spend within another farm. This total time may be split over several shorter duration blocks of time as a result of oscillating currents due to tides and eddies moving particles in and out of the farms. Thus, particles may revisit a farm several times during the number of days given on the x-axis of the figure to give the total time shown on the y-axis.

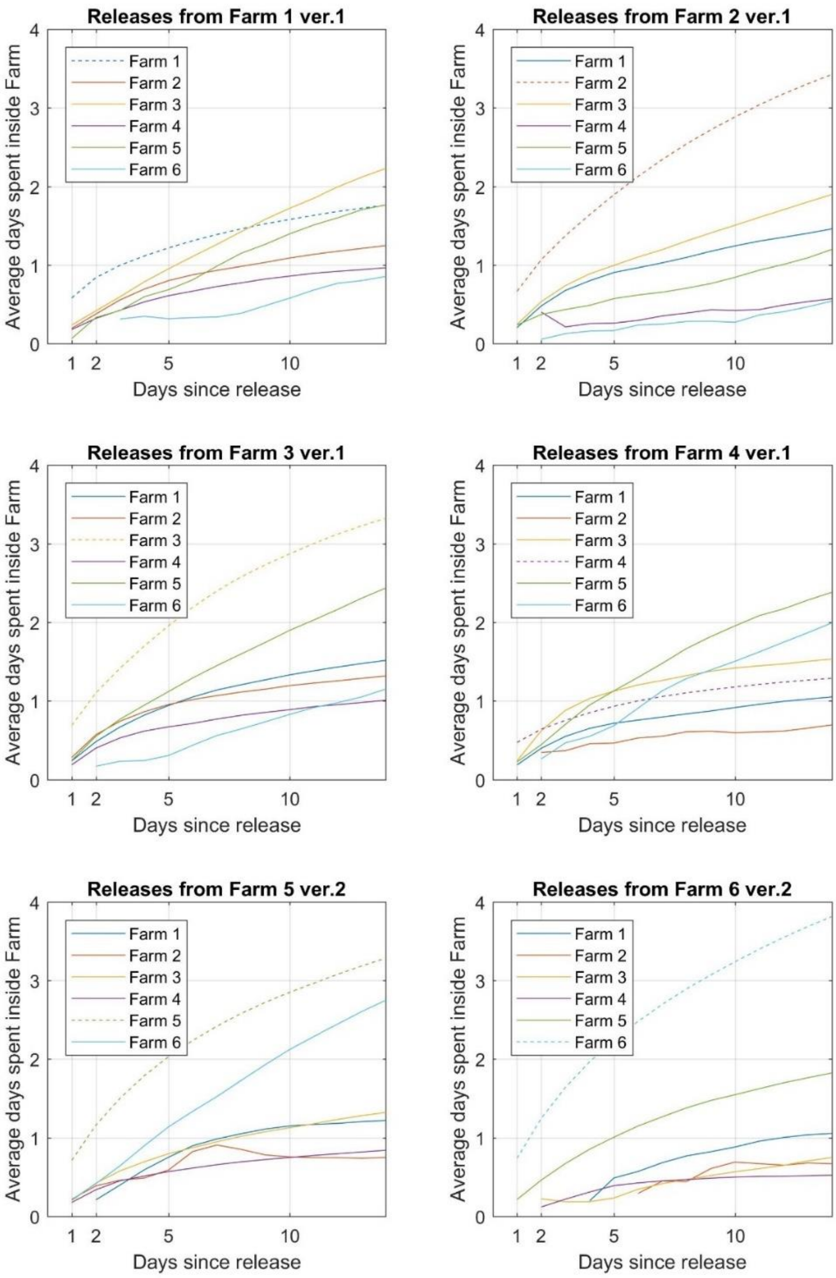

Figure A2.12. Average time in days particles released from given farm spend within another farm from forwards particle tracking. The curve for the farm from which particles were released is given by dashed lines.

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